



A study of California kneading compactors ability to optimise angular aggregate particle orientation and interlock of large stone asphalt mixes in Montana
by Robert Alexander Tipton

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University
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Abstract:

This thesis is prepared as part of phase III of Montana State University's on-going rutting study. This study is in response to the State of Montana's decaying infrastructure due to asphalt pavement rutting. The purpose of phase III is to study the effects of angular large-stone aggregates with asphalt modifiers. This thesis evaluates the effectiveness of the Marshall hammer and California kneading compactor in compacting laboratory asphalt specimens with angular large-stone aggregates. Additionally, since the kneading compactor evaluated in this study is the first ever used in Montana, details on the installation, operation, and maintenance of the compactor are included. The evaluation of the two compactors was conducted in two parts. The first part was to compare the compactors and draw general correlations relating their performances. The second part of the investigation included a detailed analysis on the aggregate sensitivity of the two compactors.

The California kneading compactor demonstrated that it produces a more consistent asphalt test specimen. Standard deviations for kneading compactor stability values were generally lower than those of the Marshall hammer. The kneading compactor and Marshall hammer were found to be very dependent on both aggregate shape and aggregate gradation. The kneading compactor produced samples with higher stabilities when using angular aggregates and a dense gradation. In contrast, the Marshall hammer specimens had higher stabilities when less angular aggregates were used with the same dense gradation. Neither compactor exhibited any specific trends with a less dense gradation. The kneading compactor's ability to provide more work to the sample during the compaction process was found to be a significant factor in the resulting stability values.

The statistical analysis used to evaluate aggregate sensitivity proved to be inconclusive. The analysis did indicate that the kneading compactor is potentially more sensitive. However, additional testing with numerous samples is required to provide conclusive data.

A STUDY OF THE CALIFORNIA KNEADING COMPACTOR'S ABILITY
TO OPTIMIZE ANGULAR AGGREGATE PARTICLE ORIENTATION AND
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APPROVAL

of a thesis submitted by

Robert Alexander Tipton

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

16 FEB 1993
Date

Joe D. Arriaga
Chairperson, Graduate Committee

Approved for the Major Department

16 Feb '93
Date

Shedee E. Lang
Head, Major Department

Approved for the College of Graduate Studies

2/19/93
Date

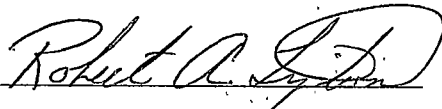
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TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	vii
LIST OF FIGURES	xi
ABSTRACT	.xiii
1. INTRODUCTION.	1
Purposes and Problem Statement.	3
2. HISTORICAL BACKGROUND.	4
Asphalt	4
Aggregates.	6
Laboratory Compactors	8
Marshall Hammer	9
California Kneading Compactor	10
Asphalt Technology in Montana	11
Summary and Hypothesis.	12
3. GUIDE FOR USING CALIFORNIA KNEADING COMPACTOR	14
Background.	14
Facility Preparation.	14
Installation.	16
Operation	18
Initial Programming of Electronic Control Panel	18
Hydraulic Control Settings.	21
Down Rate	21
Ram Low Pressure Bypass	22
Up Rate	22
Pressure Valve.	22
Ram Pressure Gauge.	23
Compactor Operation Sequence.	23
Maintenance	24
Additional Equipment Requirements	26
Kneading Compactor Cautions	27

TABLE OF CONTENTS - Continued

	<u>Page</u>
4. EQUIPMENT, MATERIAL AND PROCEDURES FOR EVALUATION	29
Overview.	29
Equipment	30
Mechanical Marshall Hammer.	30
California Kneading Compactor	31
Marshall Testing Apparatus.	32
Mechanical Shaker for RICE Tests.	33
Materials	34
Background.	34
Asphalts.	34
Aggregates.	36
Selection of Aggregate Gradations	37
Method and Procedures for Evaluation	40
Specimen Preparation	40
Specimen Testing.	42
Schedule of Tests Conducted	44
Asphalt Tests	44
Asphalt Concrete Specimen Tests	45
Method of Data Analysis	47
5. OBSERVATIONS AND RESULTS OF STATISTICAL ANALYSIS.	53
General Observations.	53
Appearance.	53
Preparation Time.	55
Stability	55
Density and Air Voids	57
Results of Statistical Analysis	58
6. DISCUSSION AND CONCLUSIONS	62
Discussion.	62
Stability	62
Density and Air Voids	63
Statistical Analysis.	65
Conclusions	66
REFERENCES CITED	69
APPENDICES	72
Appendix A - Stability Curves	73
Appendix B - Marshall Test Results.	82
Appendix C - Optimum Asphalt Calculations	95
Appendix D - Means and Standard Deviations of Samples	100

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Recommended Control Parameter Settings	21
2. Differences in MSU Apparatus Dimensions.	32
3. Phase III 1st Aggregate Gradation.	38
4. Phase III 2nd-Aggregate Gradation.	39
5. Mixing and Compaction Temperatures	42
6. Asphalt Concrete Specimen Tests.	43
7. Quality Control Asphalt Tests Conducted.	44
8. Number of Asphalt Tests Conducted.	45
9. Tests Conducted on Asphalt Specimens Compacted with the Marshall Hammer	46
10. Tests Conducted on Asphalt Specimens Compacted with the Kneading Compactor.	47
11. First Gradation "F" Test	59
12. First Gradation "t" Test	59
13. Second Gradation "F" Test.	60
14. Second Gradation "t" Test.	60
15. Entire Sample Set "Z" Test	61
16. Unmodified Kneading Compactor - 1st Gradation - Angular.	83
17. Unmodified Kneading Compactor - 1st Gradation - Round.	83
18. Kraton Modified Kneading Compactor - 1st Gradation - Angular.	84

LIST OF TABLES - Continued

<u>Table</u>	<u>Page</u>
19. Kraton Modified Kneading Compactor - 1st Gradation - Round.	84
20. Polybilt Modified Kneading Compactor - 1st Gradation - Angular.	85
21. Polybilt Modified Kneading Compactor - 1st Gradation - Round.	85
22. Unmodified Kneading Compactor - 2nd Gradation - Angular.	86
23. Unmodified Kneading Compactor - 2nd Gradation - Round.	86
24. Kraton Modified Kneading Compactor - 2nd Gradation - Angular.	87
25. Kraton Modified Kneading Compactor - 2nd Gradation - Round.	87
26. Polybilt Modified Kneading Compactor - 2nd Gradation - Angular.	88
27. Polybilt Modified Kneading Compactor - 2nd Gradation - Round.	88
28. Unmodified Marshall Hammer - 1st Gradation - Angular.	89
29. Unmodified Marshall Hammer - 1st Gradation - Round.	89
30. Kraton Modified Marshall Hammer - 1st Gradation - Angular.	90
31. Kraton Modified Marshall Hammer - 1st Gradation - Round.	90
32. Polybilt Modified Marshall Hammer - 1st Gradation - Angular.	91
33. Polybilt Modified Marshall Hammer - 1st Gradation - Round.	91
34. Unmodified Marshall Hammer - 2nd Gradation - Angular.	92

LIST OF TABLES - Continued

<u>Table</u>	<u>Page</u>
35. Unmodified Marshall Hammer - 2nd Gradation - Round.	92
36. Kraton Modified Marshall Hammer - 2nd Gradation - Angular.	93
37. Kraton Modified Marshall Hammer - 2nd Gradation - Round.	93
38. Polybilt Modified Marshall Hammer - 2nd Gradation - Angular.	94
39. Polybilt Modified Marshall Hammer - 2nd Gradation - Round.	94
40. Kneading Compactor - Phase II Aggregates - 1st Gradation - Optimum Asphalt %.	96
41. Kneading Compactor - Phase II Aggregates - 2nd Gradation - Optimum Asphalt %.	96
42. Marshall Hammer - Phase II Aggregates - 1st Gradation - Optimum Asphalt %.	97
43. Marshall Hammer - Phase II Aggregates - 2nd Gradation - Optimum Asphalt %.	97
44. Kneading Compactor - Phase III Aggregates - 1st Gradation - Optimum Asphalt %.	98
45. Kneading Compactor - Phase III Aggregates - 2nd Gradation - Optimum Asphalt %.	98
46. Marshall Hammer - Phase III Aggregates - 1st Gradation - Optimum Asphalt %.	99
47. Marshall Hammer - Phase III Aggregates - 2nd Gradation - Optimum Asphalt %.	99
48. Statistical Parameters Kneading - Unmodified - 1st Gradation.	101
49. Statistical Parameters Kneading - Kraton - 1st Gradation.	101
50. Statistical Parameters Kneading - Polybilt - 1st Gradation.	101

LIST OF TABLES - Continued

<u>Table</u>		<u>Page</u>
51.	Statistical Parameters Marshall - Unmodified - 1st Gradation.	101
52.	Statistical Parameters Marshall - Kraton - 1st Gradation.	101
53.	Statistical Parameters Marshall - Polybilt - 1st Gradation.	101
54.	Statistical Parameters Kneading - Unmodified - 2nd Gradation.	102
55.	Statistical Parameters Kneading - Kraton - 2nd Gradation.	102
56.	Statistical Parameters Kneading - Polybilt - 2nd Gradation.	102
57.	Statistical Parameters Marshall - Unmodified - 2nd Gradation.	102
58.	Statistical Parameters Marshall - Kraton - 2nd Gradation.	102
59.	Statistical Parameters Marshall - Polybilt - 2nd Gradation.	102
60.	Statistical Parameters for 1st Gradation, 2nd Gradation, and Entire Set of Samples	103

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Adhesion Properties of Aggregates	5
2. Aggregate to Aggregate Contact Properties	7
3. HMA Mixture Design Methods Used by States in the USA	8
4. Cox and Sons California Kneading Compactor.	17
5. Compactor Tamping Cycle	18
6. Electronic Control Panel.	20
7. Hydraulic Control Panel	22
8. Mold in Mold Holder with Shim	24
9. Lower Back Side of Kneading Compactor	25
10. Static Press with Specimen, Mold, and Followers	26
11. MSU - Six Inch Marshall Hammer.	30
12. MSU - Kneading Compactor with Six Inch Foot	31
13. MSU - Marshall Apparatus with Six Inch Breaking Head.	32
14. MSU - Mechanical Shaker for RICE Test	33
15. Comparison of Phase II and Phase III Aggregate.	37
16. Comparison of 1st and 2nd Gradations.	39
17. Hobart Mixer for Six Inch Asphalt Specimens	41
18. Accept Null Hypothesis.	51
19. Reject Null Hypothesis.	51

LIST OF FIGURES - Continued

<u>Figure</u>		<u>Page</u>
20.	Top and Bottom Sides of Specimen Prepared with the Kneading Compactor.	53
21.	Side View of Specimens Prepared with the Kneading Compactor	54
22.	Marshall Stabilities at Optimum Asphalt Content	56
23.	Densities at Optimum Asphalt Content.	57
24.	Air Voids at Optimum Asphalt Content.	58
25.	Comparison of Stability Curves 1st Gradation - Phase II Aggregates	74
26.	Comparison of Stability Curves 1st Gradation - Phase II Aggregates	75
27.	Comparison of Stability Curves 1st Gradation - Phase III Aggregates.	76
28.	Comparison of Stability Curves 1st Gradation - Phase III Aggregates.	77
29.	Comparison of Stability Curves 2nd Gradation - Phase II Aggregates	78
30.	Comparison of Stability Curves 2nd Gradation - Phase II Aggregates	79
31.	Comparison of Stability Curves 2nd Gradation - Phase III Aggregates.	80
32.	Comparison of Stability Curves 2nd Gradation - Phase III Aggregates.	81

ABSTRACT

This thesis is prepared as part of phase III of Montana State University's on-going rutting study. This study is in response to the State of Montana's decaying infrastructure due to asphalt pavement rutting. The purpose of phase III is to study the effects of angular large-stone aggregates with asphalt modifiers. This thesis evaluates the effectiveness of the Marshall hammer and California kneading compactor in compacting laboratory asphalt specimens with angular large-stone aggregates. Additionally, since the kneading compactor evaluated in this study is the first ever used in Montana, details on the installation, operation, and maintenance of the compactor are included. The evaluation of the two compactors was conducted in two parts. The first part was to compare the compactors and draw general correlations relating their performances. The second part of the investigation included a detailed analysis on the aggregate sensitivity of the two compactors.

The California kneading compactor demonstrated that it produces a more consistent asphalt test specimen. Standard deviations for kneading compactor stability values were generally lower than those of the Marshall hammer. The kneading compactor and Marshall hammer were found to be very dependent on both aggregate shape and aggregate gradation. The kneading compactor produced samples with higher stabilities when using angular aggregates and a dense gradation. In contrast, the Marshall hammer specimens had higher stabilities when less angular aggregates were used with the same dense gradation. Neither compactor exhibited any specific trends with a less dense gradation. The kneading compactor's ability to provide more work to the sample during the compaction process was found to be a significant factor in the resulting stability values.

The statistical analysis used to evaluate aggregate sensitivity proved to be inconclusive. The analysis did indicate that the kneading compactor is potentially more sensitive. However, additional testing with numerous samples is required to provide conclusive data.

CHAPTER 1

INTRODUCTION

Over the next few years the United States will experience a myriad of changes in asphalt technology. Current field practices reflect technology of the 1930s through the 1950s. This technology served the country well until the late 1960s when traffic volumes and loads began growing at exponential rates. These volumes and loads have seriously damaged the nation's infrastructure. This damage, combined with reduced funding for maintenance in the early 1980s, has put the country in a grave position. To restore the nation's highway infrastructure, improved technology and a dramatic increase in funding is needed.

The passing of the 1991 Federal Highway bill (ISTEA) is long overdue, and is a big step in the right direction. With this increase in financial resources, it is paramount that these funds be spent wisely on promising new technologies. Efforts of the Federal Highway Administration, transportation centers and independent agencies, all coordinated through the Strategic Highway Research Program (SHRP) have yielded many possible solutions to improved asphalt pavements. Much of this research is still being tested at field sites, such as the on-going rutting study at Montana State University.

Asphalt rutting is a failure mechanism present in many of the country's highways. Rutting is a particularly acute problem in regions

where temperature extremes are large. Eastern Montana represents an area where this problem is exhibited. Winter time lows reach sub-zero with the summer time highs at more than 100 degrees at the asphalt surface. Designing an asphalt pavement that resists both rutting and thermal cracking is a unique problem facing the Montana Department of Transportation (MDT). The on-going rutting study at Montana State University (MSU), funded by the Montana Department of Transportation is currently testing the effectiveness of large stone aggregates and asphalt modifiers. The purpose of these tests is to evaluate these materials' ability to resist rutting without increasing asphalt viscosity. If viscosity is increased, the pavement is subject to thermal cracking [1]. Of particular interest is the large stone aggregate shape. Phase III of the MSU rutting study is investigating whether angular shaped large stone aggregates provide more stability and thus are more rut resistant than large stone aggregates with rounded surfaces.

Laboratory compaction of asphalt test specimens is extremely important in studying the large stone aggregate characteristics of the test specimen. Obviously, laboratory compaction should simulate compaction as it occurs on the actual roadway. However, it is also of importance to evaluate stabilities that can be obtained by compacting specimens to the most optimum aggregate arrangement possible [2].

The state of Montana uses the Marshall method of mix design with the Marshall hammer to compact test specimens. Many other states use the California Kneading Compactor to compact test specimens. Within the asphalt field, no single laboratory compaction method has been shown to be the absolute best. Recent studies [3,4,5] indicate that the U.S. Army

Corps of Engineers' gyratory compactor and California Kneading Compactor produce a more representative sample than other compactors [4]. However, the National Center for Asphalt Technology has modified its Marshall hammer by angling the hammer head and has achieved results consistent with the kneading compactor [3]. Historically Montana has only used the Marshall Hammer to compact specimens in its asphalt pavement design.

Purposes and Problem Statement

The purpose of this investigation was to evaluate the effectiveness of the Marshall Hammer and the California Kneading Compactor in producing an asphalt test specimen that best demonstrates the optimum aggregate characteristics of Montana large stone aggregates.

This study provides the first research in Montana using the kneading compactor with Montana produced asphalt and aggregates. An additional goal of this report is to provide a guide to the Montana Department of Transportation on how to install and operate the California Kneading compactor.

This study also attempts to provide general correlations between the Marshall Hammer and the California Kneading compactor. Results from this thesis are to be used to support or refute the overall findings of the MSU Rutting Study [1] with particular emphasis on the value of angular large stone aggregates versus semi-rounded large stone aggregates found in Eastern Montana.

CHAPTER 2

HISTORICAL BACKGROUND

Asphalt

The first uses of asphalt pavement in road construction in the United States began in the late 1800s. These pavements used either tar, which is actually a distilled coal, or naturally occurring asphalt. One of the major sources of this naturally occurring asphalt came from Lake Trinidad on Trinidad Island in the Gulf of Mexico. Asphalt from Lake Trinidad was used to pave Pennsylvania Avenue in Washington D.C for the first time in 1876. By the early 1900s the petroleum industry evolved and a more uniform asphalt was produced as a by-product of the oil refining process. To this date, asphalt produced in these refineries is the major source of asphalt for asphalt pavement. While many improvements in this refining process have taken place, there is still variance from refinery to refinery.

The asphalt acts as a binder for the aggregate in asphalt pavement. It holds the aggregate together through an adhesive layer between the aggregate particles. Resistance to shear of any binder film between surfaces is proportional to the area of the film and inversely proportional to its thickness [6]. Thus, the larger the surface area in contact and the thinner the thickness of binder between those two surfaces, the stronger the bond and the greater the resistance to shear.

Asphalt also acts as a lubricant to allow some give in the pavement structure. The thicker the film, the more the pavement is allowed to move and the less strong the bond between aggregates. With this in mind, it is apparent that in asphalt pavement, it is desirable to avoid particle arrangement as shown in Figure 1(a). In this figure it can be seen that the contact area "I" is low. The arrangement shown in Figure 1(b) where contact area "I" is maximized is the most desirable. Figure 1(c) demonstrates that the contact area "I" in rounded aggregate is limited regardless of particle arrangement.

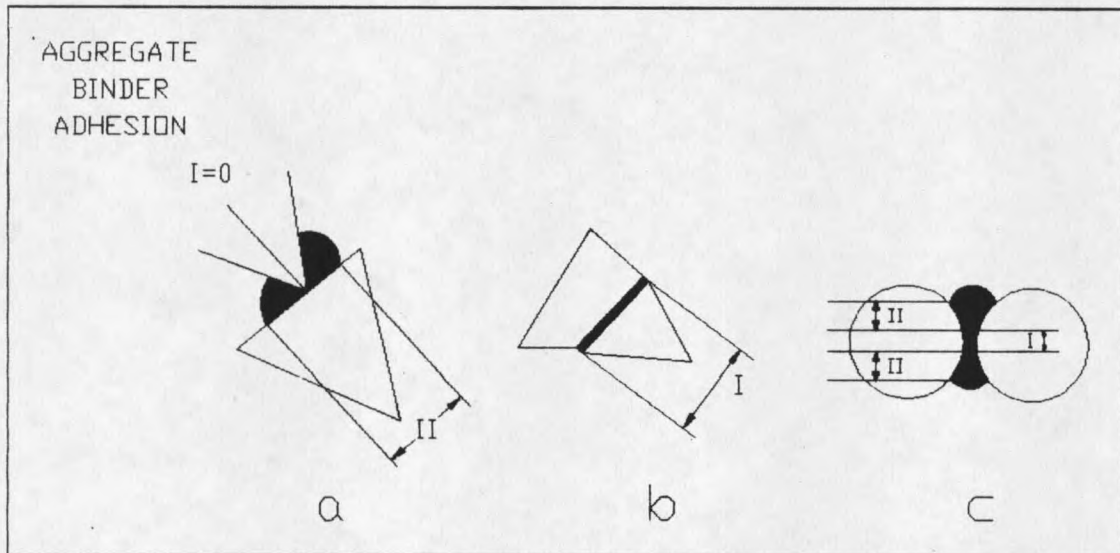


Figure 1. Adhesion Properties of Aggregates.

In recent years, asphalt modifiers have been developed. Many improve the asphalt characteristics when added. Some researchers may be putting too much stock in the benefits of modifiers in combating rutting. Asphalt modifiers can increase the binding characteristic of the asphalt which assists in resisting rutting. However, if not used with a suitable aggregate, the modified asphalt can fail as easily as an unmodified asphalt [3]. According to Robert L. Dunning, President of Petroleum

Sciences, Inc., "Rutting is caused by insufficient bearing strength of the aggregate, not a deficiency in the asphalt" [7]. The National Institute for Asphalt Technology insists that asphalt pavements must have a minimum amount of air voids to properly combat rutting [3]. Compaction, aggregate shape and gradation are key factors in the amount of air voids present in road pavements.

Aggregates

Aggregates, in asphaltic pavement, provide the actual strength and carry the majority of the loads in the pavement. "The function of the asphalt is to glue the rocks together, not carry the load, and its most important property is its ability to stress/relax by viscous flow, not its stiffness" [7]. Typically aggregate produced from an igneous rock such as basalt and dolomite are suited for use in asphalt pavement and produce pavement that is stable [3]. Phase III of MSU's rutting study is focussing on aggregate shape and its contribution to asphalt pavement's stability [1].

In the early 1900s, Frederick Warren obtained a patent for use of large stone aggregates in hot asphalt mix pavements. This patent included aggregates with an upper limit size of 3/4" to 1-1/4". This patent expired in 1920; however, due to its existence, fine grained aggregates were widely developed (1/2" or less) to avoid infringement of Warren's patent. As a result, even after Warren's patent expired, large stone mixes still were not used. The fine grained or conventional aggregate mixes exhibited excellent workability and proved to be adequate under the low tire pressures of the time. Not until the late 1960s, when tire

pressures began to increase, did asphalt mix designers start considering the use of large stone mixes to counter the rutting produced by these larger tire pressures. When using large stone aggregates, aggregate shape and gradation become increasingly more important to the asphalt pavement mix design [3,6].

Professor W.S. Housel has provided an excellent analysis of the structural effects of particles [8]. His analysis, combined with V.A. Endersby and B.A. Vallergera's article on "laboratory compaction methods and their effects on mechanical stability tests for asphaltic pavements" [6], is used in the following discussion. Referring to the spherical particles in Figure 2(a), any load applied will cause the top sphere to slip down and the others to move out. Any resistance to movement, either vertically or horizontally is provided by friction only. Comparing this to Figure 2(b) it can be seen that the vertical load is resisted by geometry, while any horizontal resistance is still a result of friction only. Finally, Figure 2(c) shows that angular particles arranged properly resist both vertical and horizontal loads through geometry. While it is understood

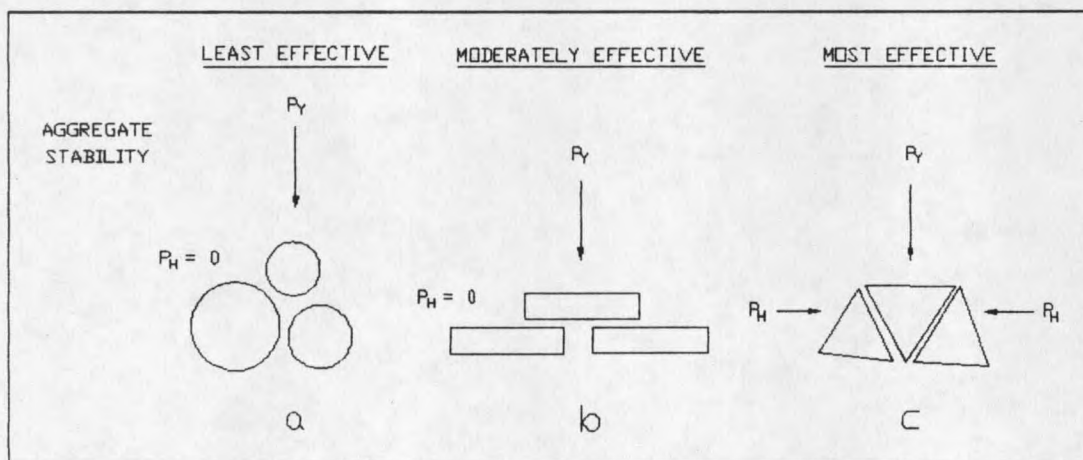


Figure 2. Aggregate to Aggregate Contact Properties.

Therefore, procedures used to prepare, mix and compact laboratory specimens deserve careful attention when evaluating the possible increased benefits of angular large stone aggregate mixes. Of particular interest is the method in which the asphalt-aggregate specimen is compacted.

In current practice the Marshall Hammer and the California Kneading Compactor are the two most common laboratory compactors used throughout the United States. Figure 3 shows the current mix design methods used by each state

[3]. The Marshall method that uses the Marshall Hammer is by far the most common method of compaction with 38 states using it. Ten states use

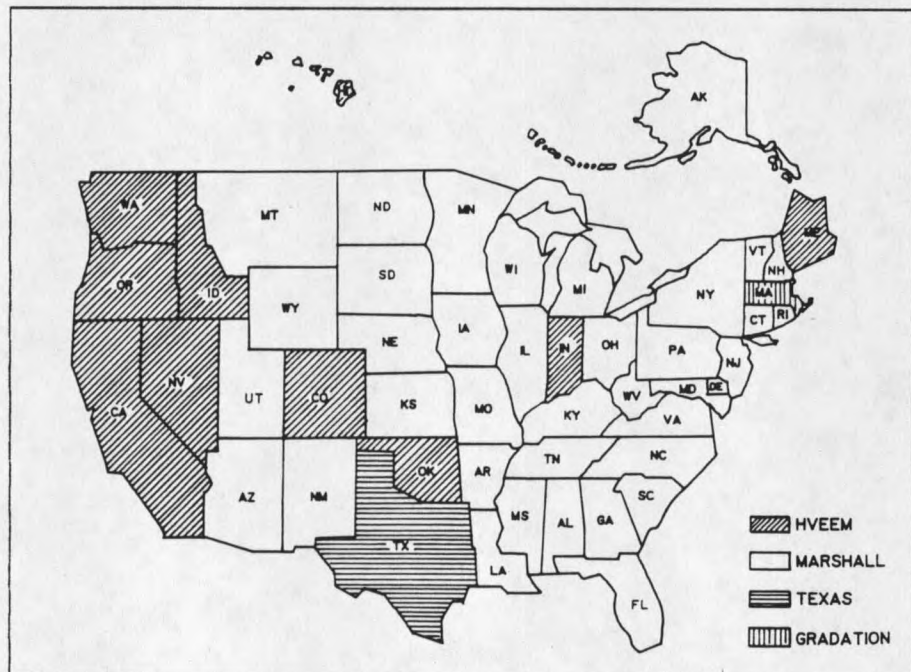


Figure 3. HMA Mixture Design Methods Used by States in the USA [3].

the Hveem method of mix design that requires the use of the kneading compactor. Texas currently is using its Texas gyratory compactor and Indiana does not use a compactor in its mix design. According to the National Center for Asphalt Technology (NCAT), the primary concept of laboratory compaction is to produce a specimen that is compacted to an air void level consistent with actual pavement in the field after it has consolidated under vehicle traffic for a reasonable period [3,9]. Often times designers and builders believe that the level of air voids achieved in the laboratory must be obtained during construction. This is in error and leads to pavement failure.

Marshall Hammer

The Marshall hammer was developed with the Marshall method of mix design by Bruce C. Marshall of the Mississippi Highway Department in the late 1930s. The U.S. Army Corps of Engineers further developed its use during the 1940s. The hammer weighs either 10 pounds (for four inch diameter specimens) or 22 pounds (for six inch diameter specimens) and compacts the hot asphalt mix through direct impact. Newer mechanical Marshall hammers also have a rotating plate that rotates the specimen as it is being compacted. The number of blows applied to the specimen is empirically derived. This number is based on the tire pressures of the traffic to which the asphalt pavement will be subjected. Large stone mixes for high pressure tires typically use 112 blows. The Marshall hammer has major advantages including ease of use, low cost, portability, and lends itself to quality control applications on the job site. Since the early 1950s, researchers have been constantly trying to develop a better method of laboratory compaction. Many feel that the direct impact

compaction of the Marshall hammer does not simulate actual field compaction well. Often, the Marshall Hammer alters the aggregate characteristics due to breakage [4,5,6]. One of the compactors developed with the purpose of better simulating field compaction is the kneading compactor.

California Kneading Compactor

The California kneading compactor or kneading compactor was introduced in association with Francis Hveem's development of the Hveem method of mix design [3]. The kneading compactor is hydraulically driven and applies pressure to the asphalt specimen with a tamper foot. The kneading compactor does not strike the sample as does the Marshall hammer, but contacts the specimen and gradually applies a specific pressure to one sixth of the sample during a specified dwell time. After each time the force is applied, the compactor rotates the specimen $1/6$ of a revolution and again applies the same amount of pressure. The idea behind the kneading compactor is to work the mix and allow the aggregate to work itself into optimum aggregate to aggregate contact rather than through direct impact as with the Marshall hammer. The kneading compactor is designed to reduce aggregate breakage during the compaction process [4,5,6,10].

During the past twenty years, gyratory compactors developed in Texas and by the Army Corps of Engineers have been acknowledged to produce samples even more representative of field construction than either the Marshall hammer or the Kneading compactor [4,5]. During the AAMAS study, the gyratory shear compactor was considered to produce a specimen that is the most representative of asphalt pavement placed in the field [5]. The

kneading compactor was second best and the Marshall hammer was rated as the least effective of the five compactors evaluated. Most states are not convinced that the gyratory compactor's slightly better test results outweigh the expense to purchase, cost to train new operators, and lack of portability for use in the field, as evidenced in Figure 3. Currently, only the state of Texas and the Army Corps of Engineers use these compactors in field practice [2,4]. As further results from field data become available, additional states may convert to the gyratory compactor.

Asphalt Technology in Montana

The state of Montana has traditionally used the Marshall Method of Mix Design with conventional sized aggregates. Typically only unmodified asphalts have been used. Montana, like the rest of the United States, has experienced increasingly higher tire pressures and traffic volumes on its state highways during the past twenty years. This increased growth with extreme temperature gradients has caused failure in many of the older highways and is causing some premature failure on more recently built roads. While current practices still reflect older technology, the state highway department is aggressively pursuing a research program to improve the state's asphalt highway infrastructure [1,11].

A prime example of the MDT's efforts in asphalt research is the "Permanent Deformation (rutting) Characteristics of Binder-Aggregate Mixtures Containing Conventional and Modified Asphalt Binders" study being conducted at MSU [1,11]. Phase I began in 1988, during which time six modifiers were tested with Montana produced asphalt and Montana aggregates. As a result, two modifiers, Kraton and Polybilt, were

selected for further evaluation. During the following year MDT and MSU established an experimental project to evaluate the modifier's performance in the field. The project was bid in August, 1990 and was constructed in the spring of 1991. Phase II continued the investigation of modified asphalt and also included large stone aggregate mixes [11].

The results of phase II prompted the current phase III which is further investigating modifiers and large stone aggregate, but focusing on the large stone aggregate shape. In phase II, the aggregate was not crushed, but the large stone used had a minimum of two fractured faces. During phase III, the aggregate was crushed and the large stone aggregate was maintained at a minimum of four fractured faces, ensuring the aggregate was very angular. MSU and MDT also decided to evaluate the California Kneading Compactor and Marshall Hammer and their ability to achieve effective aggregate to aggregate contact. Included in the funding for phase III, MDT purchased a California Kneading Compactor from Cox and Sons, Colfax, California for \$27,000.

So while the state of Montana is currently using older asphalt technology in its general field practices, it is aggressively evaluating new technologies via the Strategic Highway Program (SHRP) and has set up an opportunistic relationship with MSU to further that end. The foresight of the MDT will well prepare Montana to transition to the technology of the 1990s while improving the state's infrastructure.

Summary and Hypothesis

The current status of the state's infrastructure combined with the dynamic state of available asphalt technology has prompted the Montana

Department of Transportation to evaluate new technology and its potential for application in the field. The current practice of using conventional asphalt and aggregates is not meeting current demands, and asphalt pavement failures throughout the state have resulted. Past research indicates that asphalt modifiers and angular large stone aggregate can improve the asphaltic pavement's ability to combat permanent deformation or rutting. Recent research also indicates that the current use of the Marshall Hammer may not provide a test specimen that represents compaction in the field. The research also questions the Marshall Hammer's ability to produce test specimens that optimize the potential improved benefits of angular large stone aggregate. The California Kneading Compactor has shown that it better represents field compaction. Based on this background, the following is formulated for analysis:

The California Kneading Compactor produces an asphalt test specimen that is significantly more sensitive to aggregate characteristics than samples prepared by the Marshall Hammer. The Kneading Compactor is the compactor of choice for future research studying Montana Large Stone Aggregate and its ability to resist rutting.

This analysis is based on a level of significance of .05.

CHAPTER 3

GUIDE FOR USING CALIFORNIA KNEADING COMPACTOR

Background

The results from phase II of MSU's rutting study prompted the purchase of the first kneading compactor for use in Montana. In the spring of 1991, the kneading compactor was custom ordered through James Cox and Sons located in Colfax, California. However, it wasn't until late October that MDT approved the purchase. After purchase approval, the kneading compactor was shipped on the sixth of November and arrived to the MSU asphalt lab on 11 November, 1991. Two days later, Fred Mahlberg, a technician from Cox and Sons arrived and spent a day and a half assembling the compactor. By the afternoon of the 14th of November the kneading compactor was ready for operation. A major objective of this thesis is to document the preparation and placement into operation of the kneading compactor. This chapter should allow anyone within MDT to place the kneading compactor into operation.

Facility Preparation

The Cox and Sons kneading compactor is a large machine and the user needs to insure that an appropriate location is well thought out in advance of the kneading compactor's arrival. The compactor stands 92 inches tall and occupies an area of 43 inches by 40 inches on the floor.

An additional three feet of clearance is required behind the machine to allow for maintenance access at the rear of the compactor. The overall weight of the compactor is approximately 1500 pounds and once located is not easily moved. The kneading compactor is in no way to be considered portable. Once the proper location in the lab is determined, an electrician must prepare the electrical power source.

The kneading compactor requires two separate power lines. The first is a single phase, six AMP AC, 115 volt, 60 Hz line and the second is a three phase 15 AMP AC, 240 volt, 60 Hz line. It is advisable not to obtain power for both lines from the same source because it is not always possible to obtain the correct 115 volt single phase service from a 240 volt three phase supply. The power source requirements will not exceed 300 watts with the foot heater energized. The compactor must be grounded to insure proper operation and safety. You must insure that the machine is not run until hydraulic fluid is added and the proper hydraulic pump rotation is determined. To determine pump rotation, first add the hydraulic fluid, then turn the master switch on intermittently and check for rotation direction. The proper direction is depicted by an arrow located on the left side of the pump as it faces the back side of the kneading compactor.

Before receiving the kneading compactor, the user needs to obtain 25 gallons of either Exxon or Chevron H46 hydraulic oil or equivalent. If in use and transporting to another site, the hydraulic oil needs to be drained before shipment and, when refilled at the new site, the oil filter also should be changed. The filter used is a UCC part, part number US-1500-4-10 or equivalent.

When initially received, the kneading compactor arrived from the factory in two crates. Each box measured 50 inches by 50 inches by 60 inches with the heavier box weighing 1000 pounds. If the compactor is moved from the MSU asphalt lab, it needs to be broken down into a similar configuration before it is moved. Due to the weight and size, it is important that those receiving the compactor plan on how to move it into its new facility. As mentioned, the heavier box containing the hydraulic motor housing unit weighs more than 1000 pounds. To move the crate, the users will require a hydraulic dolly and, if the final location for the kneading compactor is above or below the ground floor, a service elevator with the appropriate weight capability is needed.

Installation

The kneading compactor has four basic sections as shown in Figure 4. Section "A" is the hydraulic motor compartment. This is the largest and heaviest single section and it houses the hydraulic motor, hydraulic fluid reservoir and rotating sample table. Section B is the computer / electrical control compartment. It houses the electrical circuit board as well as the on board computer. Section C is the hydraulic control compartment and houses the hydraulic gage as well as the controls to regulate the hydraulic movement of the compaction foot. Section D is the ram housing unit and contains the ram housing, ram and compactor foot. When initially shipped and if relocated in the future, the kneading compactor is transported with section A disconnected from sections B, C, and D. In addition, all hydraulic fluid should be drained from section A. It is recommended that the same person disassembling the kneading

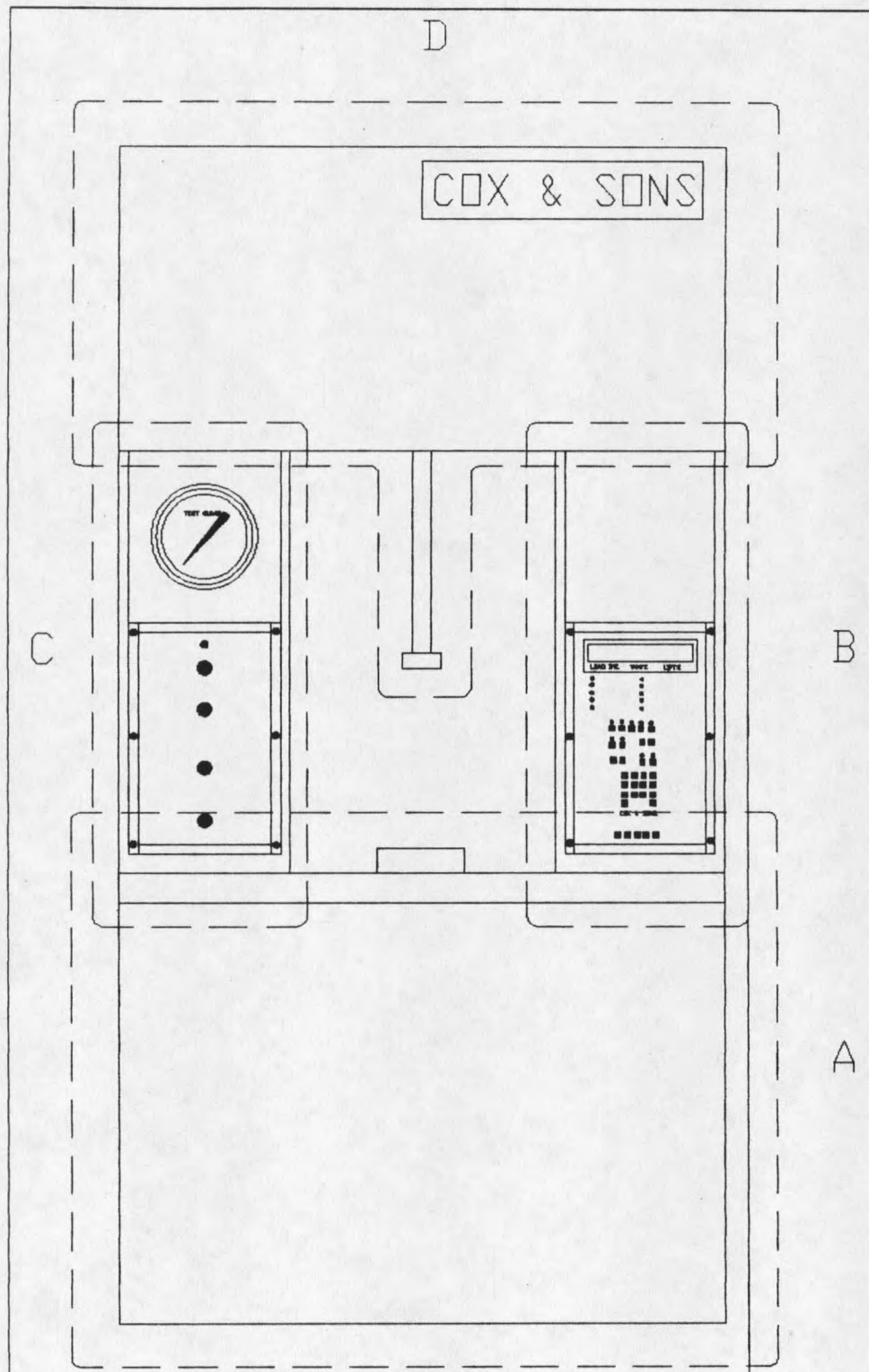


Figure 4. Cox and Sons California Kneading Compactor.

compactor before transporting it be the same person to reassemble it at its new location. If this is not possible, James Cox and Sons should be contacted so a technical representative can be present to reassemble the compactor.

Operation

The Cox and Sons Kneading Compactor is designed for both asphalt specimen compaction and preparation of soil samples for "R" value determination [12]. For this paper, only asphalt specimen compaction according to AASHTO specification T-247 [13] will be addressed. Initially the user needs to program the electronic control panel and set the controls on the hydraulic control panel. The following paragraphs on programming and operation are based on documentation notes from Cox and Sons [12].

Initial Programming of Electronic Control Panel

The electronic control panel contains the on-board computer that controls the number of tamps and the timing of the compaction cycle. Figure 5 shows the basic elements of the kneading compactor tamping cycle.

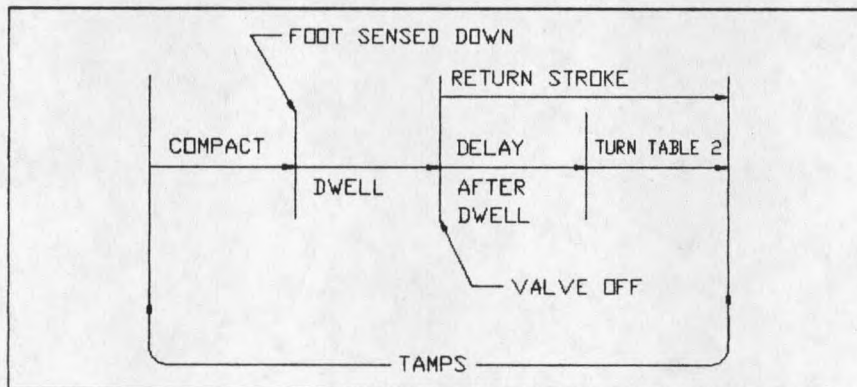


Figure 5. Compactor Tamping Cycle [12].

In the figure, the compactor initially lowers the tamping foot to the specimen until contact is made. Once contact is sensed, the tamping foot applies the appropriate pressure for a specified dwell time. After the tamping foot raises off the specimen, the specimen turn table will rotate one sixth of a turn after a programmed delay after dwell. This procedure is then repeated for the number of tamps desired at this specific cycle setting. The kneading compactor is equipped to be programmed for two separate tamping cycles. Both tamping cycles need to be programmed when compacting asphalt specimens with the kneading compactor.

A diagram showing the controls on the electronic control panel is shown in Figure 6. Refer to this figure for the following discussion on programming the compactor. To begin programming, the compactor power-on button is depressed. The hydraulics may be left off during programming. Once the compactor is on, press the compact "A" button. The small light above the button should light up and this indicates the computer is in the compact "A" mode. Now the operator has the option of activating the compaction mode by pushing the start button if one were previously programmed, modifying a previous program, or programming an initial program. To program, the stop button is then pushed to place the computer into the program entry mode. Now the up and down arrows can be pushed to display the existing settings for the control parameters listed at the top of the control panel. When the light next to an option is on, the current setting for that control parameter is displayed. To enter a new value for the displayed control parameter, the user keys in the new value on the numbered keys and then presses the enter (E) key to place it into memory. To change another control parameter the arrow buttons are used and the

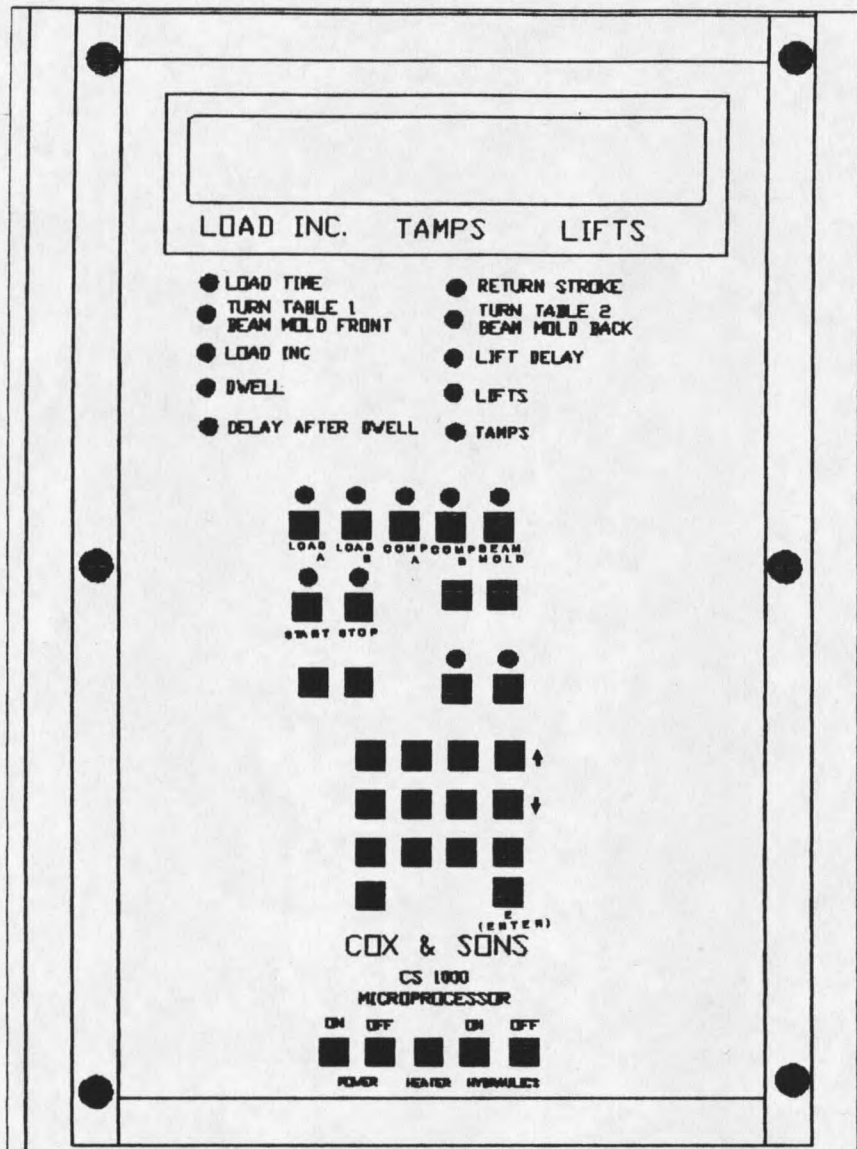


Figure 6. Electronic Control Panel (Section B).

same procedure is followed. Once all control parameters are set for the compact "A" mode, the stop button is pushed again. To program the compact "B" mode, press the compact "B" button, then press the stop button and repeat the procedure as done for the compact "A" mode. Only the compact "A" and compact "B" modes are used during asphalt specimen compaction. The load "A" and load "B" modes are associated with soils test specimens and

will not be discussed in this paper. To compact asphalt specimens according to AASHTO T-247, the settings listed in Table 1 are recommended.

TABLE 1. Recommended Control Parameter Settings.

Control Parameter	Compact "A" mode	Compact "B" mode
Dwell	0.4 - 0.5	0.4 - 0.5
Delay after Dwell	0.3	0.3
Return Stroke	0.6 - 0.8	0.6 - 0.8
Turn Table 2	0.5 - 0.6	0.5 - 0.6
Tamps	30	150

The Compact "A" mode represents semi-compaction of the sample as described in AASHTO T-247 [13]. The sample is compacted for approximately 25 tamps at 250 PSI before the full compaction of 500 PSI is applied for 150 tamps [13,14]. The additional five tamps programmed allow the operator five tamps to adjust the ram pressure from 250 PSI to 500 PSI so the sample receives exactly 150 tamps at 500 PSI during the Compact "B" mode.

Hydraulic Control Settings

The hydraulic controls are located in section C of Figure 4. The hydraulic control panel is shown in detail in Figure 7. Before initiating any compaction cycle, the hydraulic settings should be checked to insure they are properly set.

Down Rate (Ram Velocity). This dial sets the rate at which the ram is lowered to the specimen. For six inch diameter asphalt samples, it is important that the down rate is reduced as low as possible. If the down rate is high, the ram actually strikes the asphalt specimen with an impact

action similar to the Marshall hammer. The purpose of the kneading compactor is to work or knead the sample not strike it like an impact compactor. Turn this control clockwise to decrease and counterclockwise to increase.

Ram Low Pressure Bypass. The ram low pressure bypass is only needed at low foot pressures. It is used to increase the downward velocity of the ram at low pressures and is not of concern when compacting asphalt specimens according to AASHTO specification T-247 [13].

Up Rate (Ram Velocity). The up rate controls the velocity of the ram foot as it raises of the sample. The only reason to increase this rate is to reduce the overall time to compact the sample. It is recommended to set the up rate at a moderate velocity. To increase the up rate, turn the control counterclockwise.

Pressure Valve. The pressure valve is the most used dial on the hydraulic control panel. This valve controls the ram pressure as indicated on the ram pressure gauge. The operator must manually reset

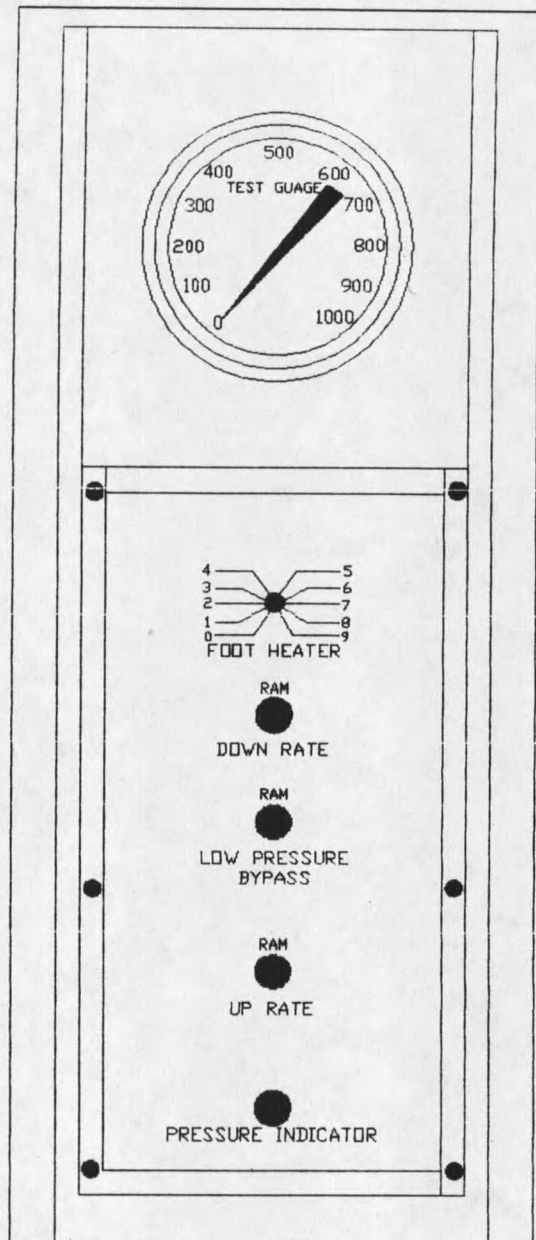


Figure 7. Hydraulic Control Panel.

this valve each time between the 250 PSI semi-compaction mode and the 500 PSI full compaction mode.

Ram Pressure Gauge. This gauge measures the pressure on the specimen. The gauge measures pounds per square foot applied to four inch samples with the smaller 3.1416 square inch tamping foot. When compacting four inch samples, the operator sets the pressure as it is read right off the gauge. When compacting six inch samples, a larger tamping foot, which measures 6.0319 square inches, is used. The gauge reading must be converted for the larger size ram foot by multiplying the gauge reading by 1.92 ($6.0319/3.1416$). During the semi-compaction mode, the pressure gauge should be set at 480 for six inch samples. At this reading the sample is actually receiving a pressure of 250 PSI. During the full compaction mode, the pressure gauge should read 970 which means the sample is receiving a pressure of 500 PSI.

Compactor Operation Sequence

Approximately 30 minutes before compacting samples, the power switch should be turned on. Once the power is on, the foot heater is turned on. The foot heater setting varies depending on the amount of asphalt present in the specimen. For asphalt percentages of 2%-4.5% a setting of 5 is recommended. For asphalt percentages of 4.5%-8% a setting of 6 is advised. After 30 minutes, the foot heater should be sufficiently warm so the asphalt will not stick to the ram foot during compaction. The hydraulics switch is then turned on.

Specimens are then prepared according to the mix procedure being used. The specimen is placed in the mold and the mold holder with 1/8"

shim and mold tightening screw tightened as shown in Figure 8. It is then compacted with the kneading compactor as outlined in AASHTO specification T-247 [13]. For semi-

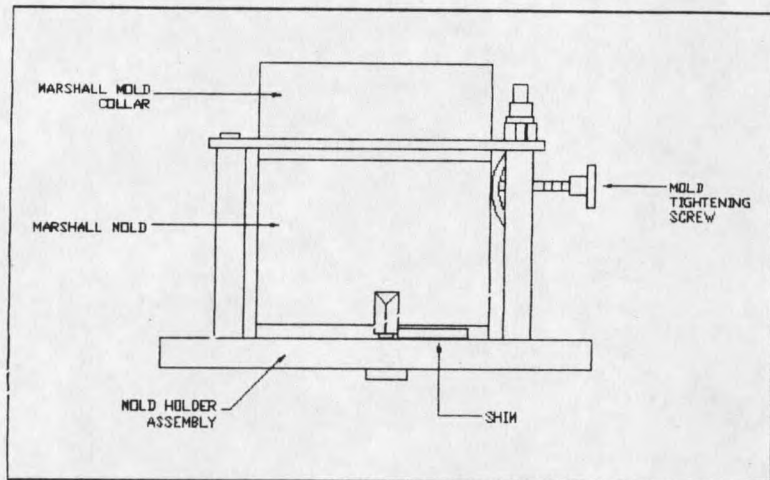


Figure 8. Mold in Mold Holder with Shim.

compaction, the operator then selects COMP "A" and then presses start. As the compactor begins, the pressure valve is adjusted so the specimen is receiving 250 PSI (480 for six inch specimens). After the 25th tamp, the pressure is then increased so by the 30th tamp the gauge reads 500 PSI (970 for six inch specimens). After the specimen is semi-compacted, the tightening screw is loosened and the shim is removed. The operator presses COMP "B" and the kneading compactor automatically applies 150 tamps at 500 PSI. Regardless of mix procedure, the mold with the sample is removed from the mold holder and placed in an oven at 60 degrees Celsius for one and a half hours to cure. After curing, a 1000 PSI leveling off load is applied by the double plunger method. The sample is then ready for testing in accordance with whichever testing method is chosen.

Maintenance

Operator maintenance of the kneading compactor is relatively simple. There are only a few important items the operator should keep in mind when

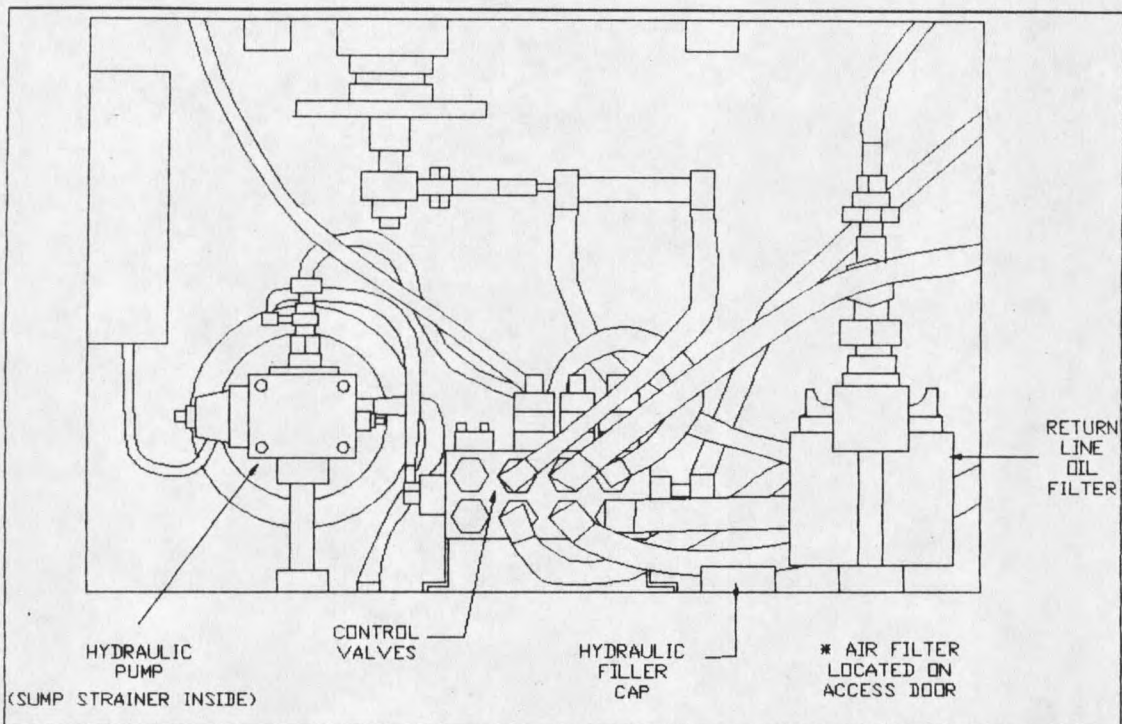


Figure 9. Lower Back Side of Kneading Compactor.

using and maintaining the compactor. First, all personnel who are to operate the compactor need to understand the operating instructions completely. The first step to good maintenance is to operate the kneading compactor as it is designed to work. An important rule of maintenance is to insure that the compactor is kept clean. Testing with asphalt is unclean. If asphalt is allowed to build up on the controls, gauges, ram or compaction table, the probability of equipment failure is going to be increased.

The following items are concerned with the back part of the machine as shown in Figure 9. The twenty - five gallons of H46 hydraulic oil should be changed at least every ten thousand hours. The oil level in the reservoir needs to be checked every 200 hours. The oil level is maintained between the 1/3" to 1-1/2" above the bottom of the filler screen which is located directly inside of the filler cap. The oil filter

should be changed every 1000 hours of operating use. Finally, the air filter should be cleaned every 500 hours; more frequently if the machine is operated under dusty conditions.

Additional Equipment Requirements.

In addition to the kneading compactor, several other items of equipment are needed. This equipment is not used with a Marshall hammer.

After the asphalt test specimen is compacted with the kneading compactor, it must cure in an oven set at 60 degrees Celsius. This temperature does not coincide with the mixing temperature so the ovens used to heat the asphalt and aggregates before mixing cannot be used. This means that an additional oven is required.

A 1000 PSI static load also must be applied to the specimen after it has cured. A simple hydraulic press can accomplish this task. A minimum of 28,300 pounds of direct pressure is required to properly press six inch specimens. A 20 ton

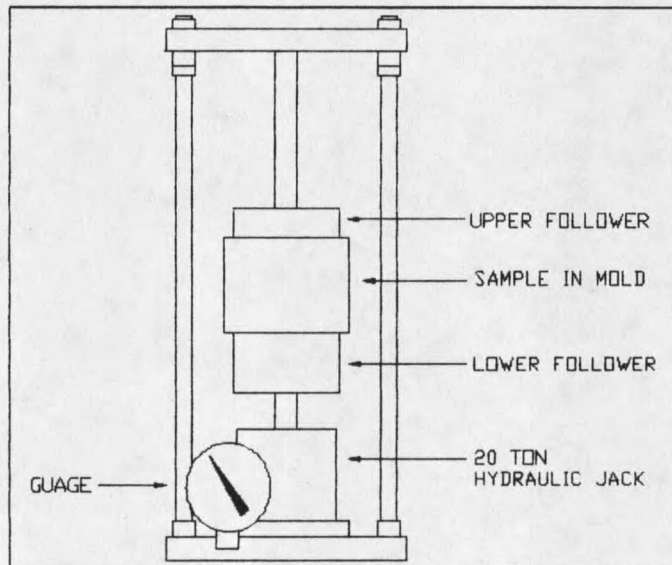


Figure 10. Static Press with Specimen, Mold and Followers.

and mounted with a support system as shown in Figure 10 proved to be sufficient. A press like this can be purchased from test equipment manufacturers. However, one can be built at a fraction of the cost. To

compress the specimen by the double plunger method, an upper and lower follower for both four inch and six inch molds is needed. For four inch molds, the larger follower should be 3.985 inches in diameter and 5.5 inches tall. The smaller follower has the same diameter but is only 1.5 inches tall. For six inch molds, the larger follower is 5.985 inches in diameter and 5.5 inches tall. The smaller six inch follower is 5.985 inches in diameter and is 1.5 inches tall. The followers are used with the mold and press as shown in Figure 10.

Four inch molds designed for use with the kneading compactor can be purchased from test equipment manufacturers. However, no special molds are currently available for six inch specimens. Initially, three four inch molds were purchased and three CBR soil molds were modified for use as six inch molds. It was thought that the kneading compactor needed a taller mold than that of the Marshall hammer. After experiencing difficulty with the CBR molds, an attempt was made to use six inch Marshall molds. The result showed that the Marshall molds worked better. The mold collars are used during the semi-compaction mode and then removed before the full compaction. The shorter mold was much easier to handle when applying the 1000 PSI static load. Also, since the lab already had 12 six inch Marshall molds, the production rate was increased at no additional cost.

Kneading Compactor Cautions.

When turning on the kneading compactor, the electronics should always be turned on before activating the hydraulics. This prevents the ram from inadvertently coming down under pressure. Always ensure the hydraulics

switch is off before the operator places his hands beneath the ram.

The kneading compactor has a very sensitive gauge. If the pressure valve is set so the pressure exceeds the maximum limit of the gauge, the gauge will be damaged and may fail. The initial gauge sent with the compactor was only rated at 1000 PSI and was operated at 960 to compact six inch samples. While this was not at the maximum 1000 PSI, it was close enough to cause failure. Over time, occasional spurs that sent the gauge over 1000 PSI, caused the gauge to fail twice. As a result, the 1000 PSI gauge was replaced with a 1500 PSI gauge. Caution should still be taken to ensure the pressure valve is never opened to a point that may cause gauge failure.

CHAPTER 4

EQUIPMENT, MATERIALS AND PROCEDURES FOR EVALUATION

Overview

Although the Marshall hammer and the kneading compactor typically produce asphaltic pavement specimens using different mix procedures, only the Marshall Method of Mix Design and Marshall testing methods were used in this thesis to evaluate the two compactors. The kneading compactor has historically been used in conjunction with the HVEEM method of mix design and associated tests, however to hold outside variables constant only one mix design was used. Additionally, normal Marshall Mix Design samples are only four inches in diameter and were designed primarily for use with conventionally sized aggregates. When using large stone aggregates, six inch specimens must be produced for analysis. Current AASHTO specifications only address the preparation of four inch samples.

The Pennsylvania Department of Transportation developed the equipment and procedure for preparing and testing six inch diameter specimens, in compliance with the general recommendation that the diameter of the mold should be at least four times the maximum nominal diameter of the coarsest aggregate in the mixture [18]. In general, the same procedures are followed for the preparation and testing of the six inch Marshall test specimens as for four inch specimens. The six inch mold is 3 and 3/4 inches tall which gives the same diameter/height ratio as the

four inch mold.

Equipment

Numerous associated equipment was used in the overall testing including various ovens, scales, water baths, and probes. All equipment used, met the specifications listed for each test conducted as outlined in the 1990 AASHTO manual [13]. The major pieces of equipment studied include a mechanical Marshall Hammer and a California Kneading Compactor. The Marshall apparatus with a breaking head for six inch samples was used to measure Marshall stabilities and flow, and the maximum specific gravity tests were conducted using a mechanical shaker developed through the innovations of the MSU asphalt lab personnel.

Mechanical Marshall Hammer

The Marshall Hammer at MSU is a mechanical hammer designed to compact six inch asphalt specimens and is shown in Figure 11. The impact hammer weighs 22.5 pounds and is dropped from a distance of 18 inches above the sample. The apparatus also automatically rotates the sample as it is compacted as well as counts the number of blows provided. For large

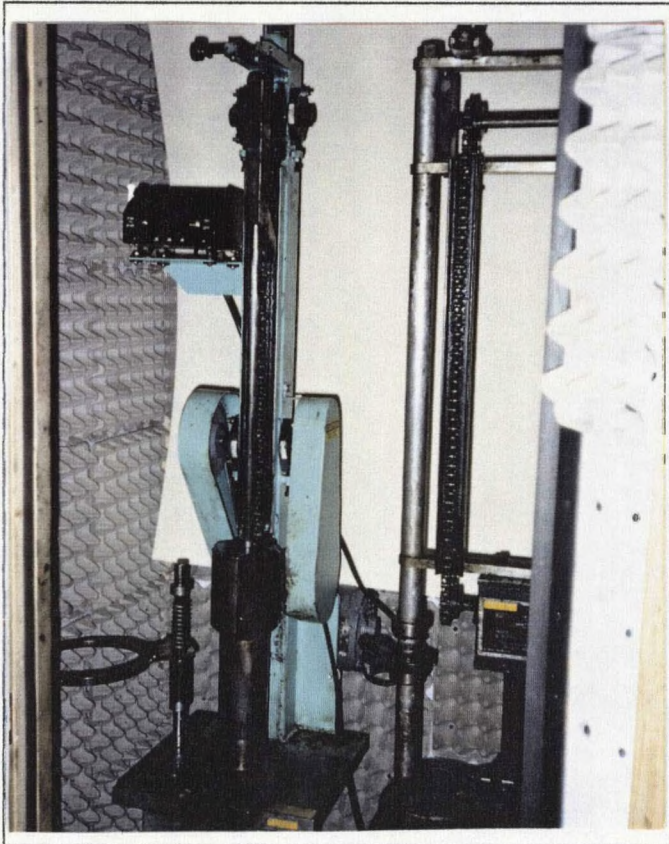


Figure 11. MSU - Six Inch Marshall Hammer.

stone mixes, 112 blows were applied to each specimen in order to simulate high tire pressure compaction conditions [1]. When the six inch samples receive 75 and 112 blows, it is equivalent to the energy input per unit volume of the four inch samples receiving 50 and 75 blows respectively.

California Kneading Compactor

Figure 12 shows the California Kneading Compactor at MSU that was built and delivered by Cox and Sons Inc. in 1991. This compactor represents the most recent developments associated with kneading compactors. It is hydraulically driven and contains an on board computer which monitors and controls all of the compaction parameters as outlined in chapter 3 of this thesis.

The kneading compactor foot for four inch samples has a contact area equalling 3.142 square inches. For six inch samples this foot is replaced by a larger 6.032 square inch foot.

The total force is adjusted on the kneading compactor so that the overall pressure is the same for both four and six inch samples. The same six inch specimen molds used with the Marshall hammer were used with the kneading compactor.



Figure 12. MSU Kneading Compactor with Six Inch Foot.

Marshall Apparatus

The Marshall apparatus at MSU was manufactured by Soiltest. The special six inch breaking head used to test large stone samples was manufactured by the Pine Instrument Company. The Marshall apparatus can be used with either the traditional four inch breaking head or the six inch breaking head as shown in Figure 13. The six inch breaking head meets all the specifications as outlined in reference [18], except

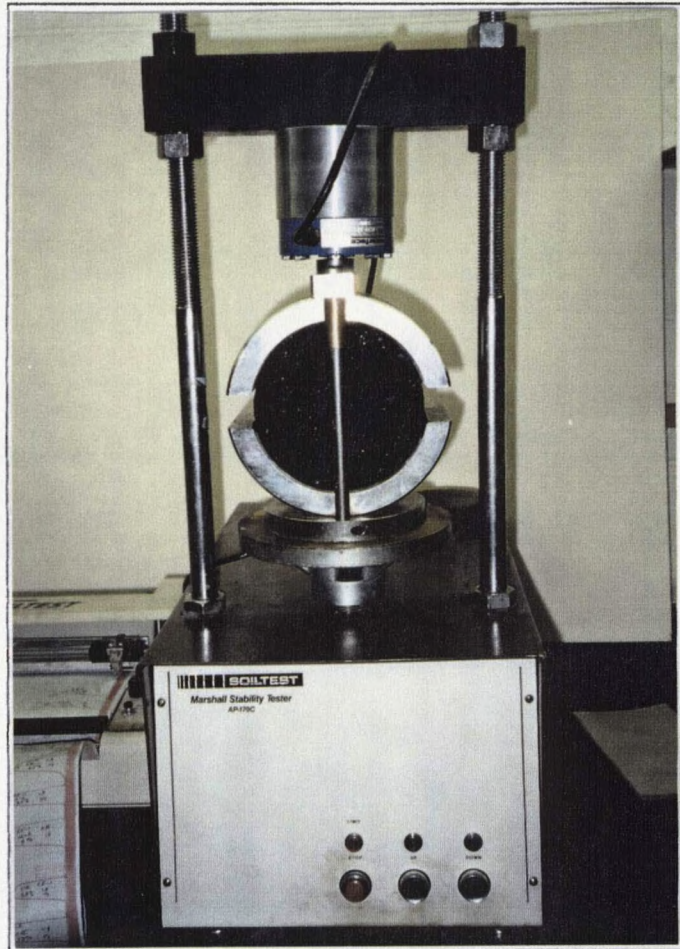


Figure 13. MSU Marshall Apparatus w/Six Inch Breaking Head.

for dimensions of the base plate, hammer, and breaking head. Table 2 lists these differences.

TABLE 2. Differences in MSU Marshall Apparatus Dimensions.

	Specified Measurement	Actual Dimension of MSU Apparatus
Base Plate Thickness	.25"	.16"
Compaction Hammer Diameter	3.0"	2.90"
Compaction Base Diameter	5.88"	5.97"
Breaking Head Width	4.88"	4.5"
Breaking Head Thickness	.87"(min)	.95"

Mechanical Shaker for Maximum Specific Gravity Tests

Because of the enormous amount of Maximum Specific Gravity (RICE) tests that needed to be conducted during phase III, the lab technicians at MSU adapted a Red Devil paint shaker to automatically agitate the asphalt specimens as shown in Figure 14.

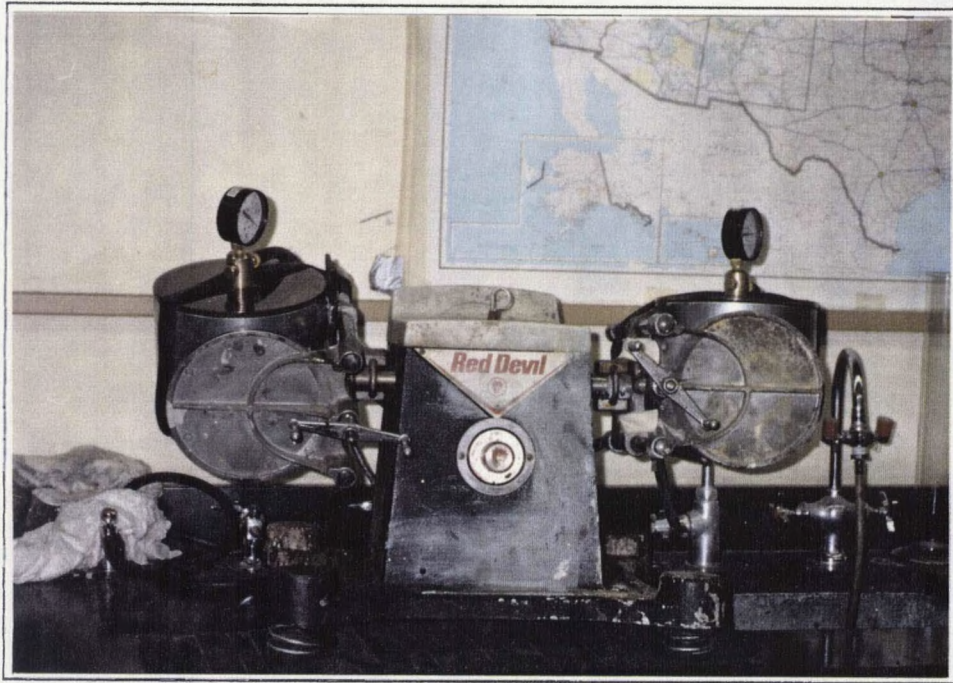


Figure 14. MSU Mechanical Shaker for RICE Test.

In addition to modifying the clamping devices to hold the RICE pycnometer, an automatic timer was built to activate the shaker at the appropriate intervals as outlined in AASHTO test T209-90 [13]. AASHTO states that the samples in the pycnometer be agitated vigorously every two minutes for 15 minutes give or take two minutes. Prior to the implementation of the mechanical shaker, it was found that each technician shakes the pycnometer differently and this resulted in unacceptable variance in RICE results. After implementation of the mechanical shaker, the RICE results became much more consistent and thus less repeats were

required.

Materials

Background

Throughout the study, the selection of materials has evolved through the various phases, resulting in the current materials used in phase III. During phase I of the study [19], which was conducted in 1990, two different Montana asphalts were tested with various asphalt modifiers and conventional aggregates. Results from phase I indicated that two modifiers were very effective when combined with the Montana Asphalts and aggregates. During phase II [11], the same asphalts combined with the recommended modifiers from phase I were used with large stone aggregates. This led to the current aggregate selection for phase III which is identical to that of phase II in terms of mineralogy. However, during phase III the large stone aggregate was completely crushed and the large stones were required to have at least four fractured faces resulting in very angular aggregate.

Asphalts

Asphalt cement (120/150 penetration grade) from Cenex Refinery in Laurel, Montana and the Conoco Refinery in Billings, Montana were selected for this investigation. The two refineries were observed to be the most diverse during phase I [19] of the MSU rutting study. Samples of unmodified asphalt from both refineries were obtained. Both asphalts were also modified by the manufacturers as described below and then shipped to Montana State University.

Kraton Modified Asphalt

Kraton rubber-asphalt mixtures were prepared by Shell Development Company utilizing 4.3% and 6% w neat Kraton D4141G. Each make of asphalt; Cenex and Conoco, was modified with the Kraton 4141G polymer. Kraton thermoplastic rubber polymers are a unique class of rubber designed for use without vulcanization. They differ fundamentally in molecular structure from the typical plastic or commercial rubber, in that they are triblock copolymers with an elastomeric block in the center and a thermoplastic block on each end. They are readily soluble and thus are suited to the formulation of solvent-based adhesives. D4141G is a linear SBS (Styrene-Butadiene-Styrene) of block copolymers similar in molecular architecture to D1101. The "D" designation refers to either SBS or SIS polymers. The first "4" identifies the polymer as containing process oil, usually a naphthenic/paraffinic type which is added to the polymer to aid in the mixing of the polymer into the bitumen and to effect desirable changes in the physical properties of the final binder blend. D4141G contains about 29% oil. The designation "G" refers to the polymer being in the ground "powder" form again for the purpose of decreasing blending time.

Polybilt Modified Asphalt

Polybilt is an Ethylene Vinyl Acetate (EVA) resin and encompasses a large family of petrochemical polymers and polymer concentrates designed for asphalt modification by Exxon Chemical Company. Two polymers were used, Polymer #2 and Polymer #7; both are EVAs but differ in molecular weight and vinyl acetate content. Polymer #2 was used for the Cenex asphalt and Polymer #7 for the Conoco asphalt. The treat rate was 4% and

3.5% by weight for the Cenex and Conoco asphalts respectively. The reason that different polymers were used was because the Conoco asphalt exhibited more synergy with Polybilt than the Cenex asphalt.

Aggregates

The objective of using large stone aggregate mixtures is to change the basic structure of the mix such that the traffic load is supported by direct stone on stone contact [20].

The selection of aggregate type was made during phase II of the rutting study. This selection was made after conferring with the Montana Department of Transportation materials personnel in Helena, Montana. Since rutting problems are more pronounced in the eastern areas of the state and the pavements historically have used gravel from the Yellowstone River, aggregates from the Yellowstone River Valley were selected. During phase II, Montana State University received conventional material from the E.E. St. Johns Pit out of MDT's Billings District. The large stone aggregate used during phase II was provided by the Prince Paving Company out of Forsyth, Montana and was also Yellowstone River aggregate. All aggregates used during phase II were obtained in their natural state, or in other words were not crushed. The large stone aggregates used, had a minimum of two fractured faces. Other than the large stone aggregate, the aggregates were mostly rounded, thus, the overall shape of the phase II aggregates was, at best, only semi-angular.

As discussed in chapter two of this thesis, if an angular aggregate is arranged properly, it should provide a more stable mixture than that of a round or semi-angular aggregate. This is the basis for the choice of a crushed or very angular aggregate for use in phase III. Again, the E.E.

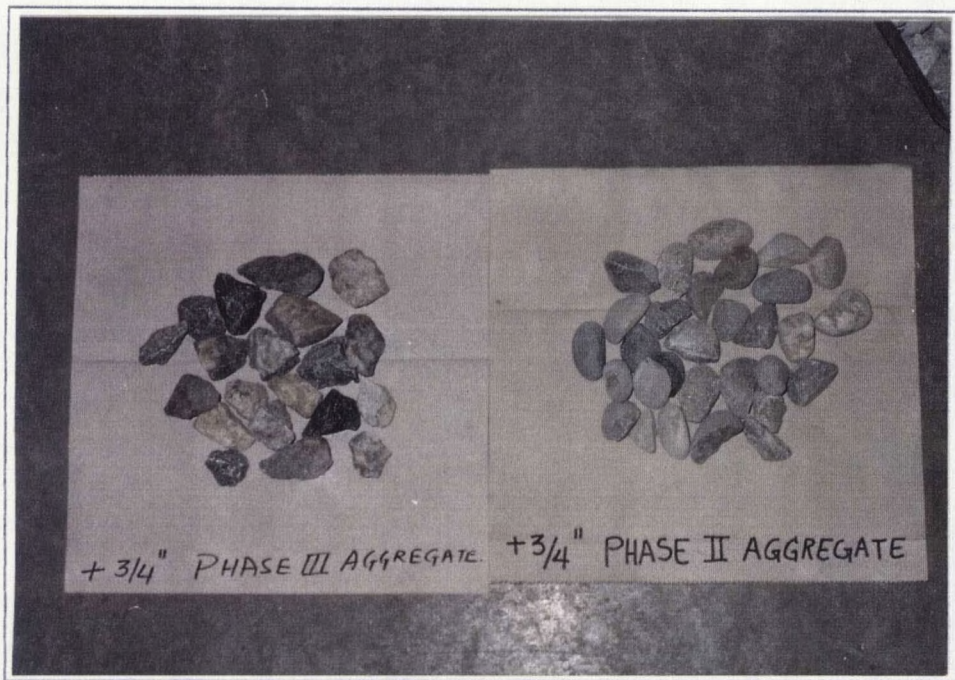


Figure 15. Comparison of Phase II and Phase III Aggregate.

St. Johns Pit in eastern Montana was selected to obtain Yellowstone River gravel for testing. However, once the rock was excavated, it was transported to an impact crusher operated by Kenyon Noble in Bozeman, Montana. The rock was then crushed to obtain crushed large stone, coarse and fine material. The impact crusher produced well formed cubical aggregates. Only crushed material was used, to include crushed fines. Most of the aggregates under $\frac{1}{2}$ inch were crushed to cubical shape with all fractured faces. The larger aggregate between $1\frac{1}{2}$ inch and $\frac{1}{2}$ inch had some non-fractured faces, but were cubical in shape. During sieving all large stone was maintained at a minimum of four fractured faces through visual inspection. A comparison between phase II and phase III aggregate is shown in Figure 15.

Selection of Aggregate Gradations

The selection of the large stone aggregate mix gradations was done

during phase II of the rutting study [11]. This selection was based on in house tests and experience gained in other states. Large stone is defined as an aggregate with a maximum size of more than one inch.

For the first gradation, a trial set of Marshall mix design tests with three different gradations was conducted. The first trial gradation represented the maximum density and fell right on the 0.45 power curve. The second trial gradation was a hump gradation at the #30 sieve size and the final trial gradation was a skip or gap gradation. The Marshall test results showed that maximum stability and density were achieved with the first gradation or the maximum density gradation. Thus, this gradation was selected as the first gradation (See Table 3).

TABLE 3. Phase III 1st Gradation.

SIEVE SIZE	PERCENT RETAINED	WEIGHT IN GRAMS
1"	16.6%	639.4
3/4"	10.6%	406.9
1/2"	12.1%	465.0
3/8"	7.6%	290.6
#4	14.6%	561.9
#8	9.6%	368.1
#16	8.5%	329.4
#30	5.5%	213.1
#200	9.6%	368.1
-#200	5.3%	202.5

Eight states have had experience in the application of large stone mix designs which include Arkansas, California, Colorado, Kentucky, Oklahoma, Tennessee, Texas and Wyoming [18]. The specifications of the

aggregate mix gradations of all eight states were reviewed and plotted in an aggregate gradation chart. It was found that the specification of the state of California, as shown in Table 4, represents the median value specification. This gradation was selected as the second gradation.

TABLE 4. Phase III 2nd Gradation.

SIEVE SIZE	PERCENT RETAINED	WEIGHT IN GRAMS
1"	8.5%	329.4
3/4"	11.5%	445.6
3/8"	17.5%	678.1
#4	21.5%	833.1
#30	24.0%	930.0
#200	12.5%	484.4
-#200	4.5%	174.4

Both gradations are shown plotted on the .45 power curve in Figure 16.

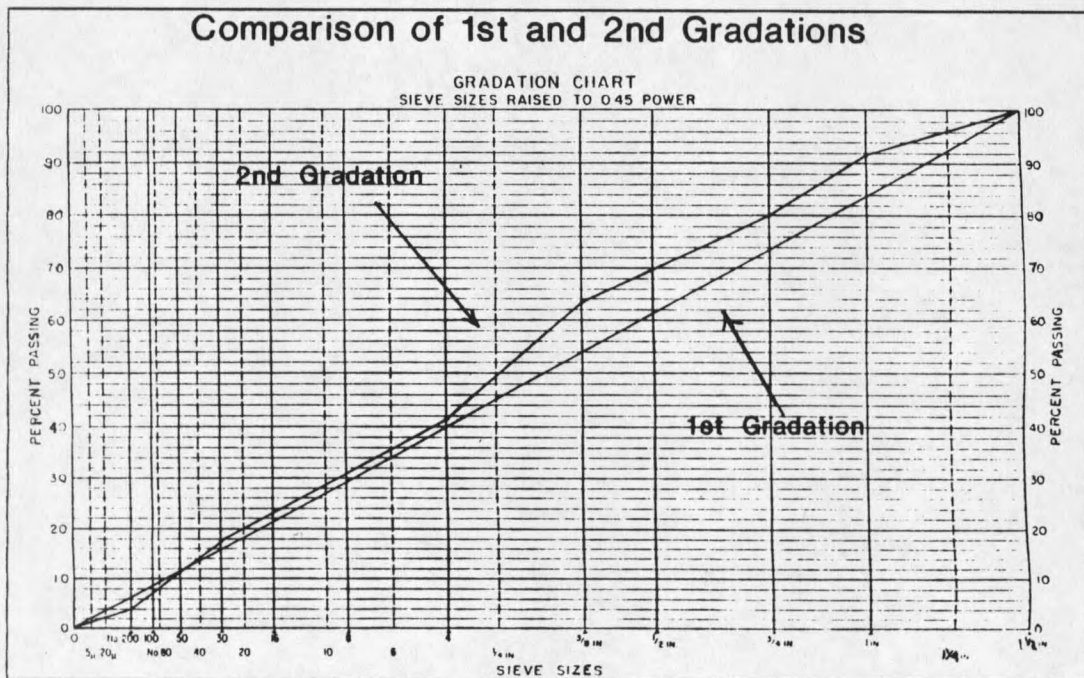


Figure 16. Comparison of 1st and 2nd Gradations.

Method and Procedures for Evaluation

Specimen Preparation

The Marshall Method of mix design is an empirical method of determining mix proportions for asphalt concrete and is the sole method used in this thesis. Prior to specimen preparation, a range of trial asphalt contents must be selected. This range of trial asphalt contents must contain the peak or maximum stability when tested with the Marshall apparatus. Based on the results from phase II [11], asphalt percentages of 3.5%, 4.0%, 4.5% and 5% were selected. The aggregate was dried, separated and weighed to obtain the desired mix in accordance with the appropriate selected gradation. Three specimens for each combination of asphalt content and aggregate were prepared and the test results averaged from the three specimens.

The weighed out samples were then placed in aggregate ovens and heated to approximately 350°F. The asphalt was also preheated in an asphalt oven to approximately 140°C. Once the aggregate and asphalt were at the prescribed temperatures, the appropriate percentage, by weight, of asphalt was mixed with the aggregate in a preheated mixing bowl. Prior to adding the asphalt the dried aggregate was thoroughly mixed. Once the asphalt was added to the aggregate, the entire mixture was then completely mixed using a Hobart mixer for approximately 1.5 minutes as shown in Figure 17. During the mixing, the technician continuously worked the mixture to insure complete coverage of the asphalt on the aggregate.

After the specimen was mixed it was transferred to a six inch marshall mold. The molds and spatulas were cleaned and preheated on a hot plate to about 250°F prior to mixing. If the specimen was to be compacted



Figure 17. Hobart Mixer for Six Inch Asphalt Specimens.

with the Marshall hammer, the hammer was also cleaned and preheated on the hot plate at 250°F. The technician placed a filter paper on the base of the mold to eliminate potential sticking when the specimen was later removed from the mold.

The mixture was then placed in the mold in two stages. About half of the mixture was initially added to the mold and then was tamped with a heated spatula ten times over the interior of the mold and 15 times around the perimeter. The second half of the mixture was then added and tamped the same as the first half. If the specimen was compacted with the Marshall hammer, an additional filter paper was added to the top of the mold. This additional filter paper was not necessary if the specimen was compacted with the kneading compactor. Also, if using the kneading compactor, the mold was preheated inside the mold holder (See Figure 8 on page 24).

At this point, the specimen temperature was checked. This temperature was the compaction temperature and was the most critical step of the process. If the temperature was not within the prescribed compaction temperature, the specimen was rejected and the process was started over. The mixing and compaction temperatures were predetermined based on viscosity tests conducted during phase II [11] (See Table 5).

TABLE 5. Mixing and Compaction Temperatures.

ASPHALT TYPE	COMPACTION TEMPERATURE
CENEX	284 - 296° F
CONOCO	277 - 285° F

The mixing and compacting temperatures were used for both the unmodified and modified asphalt specimens.

For samples compacted with the Marshall hammer, the specimen was then placed on the compaction pedestal and 112 blows of compaction were applied. The mold assembly was then reversed and an additional 112 blows were applied to the other side of the specimen. The specimen was then allowed to cool to room temperature in the mold and then removed from the mold using a sample extractor.

For specimens compacted with the kneading compactor, the procedure outlined in chapter three under compactor operator sequence on page 24 was followed. After the kneading compactor samples were cooled they were also removed from the mold using the sample extractor.

Specimen Testing

Each specimen prepared was tested to determine Marshall stability, Marshall flow, bulk specific gravity, density, maximum specific gravity

(RICE), and percent air voids present in the sample. Table 6 lists the associated AASHTO tests [13] conducted to determine the required characteristics of the asphalt samples.

The tests listed in Table 6 were conducted exactly as outlined in the AASHTO manual [13], except for the deviations in equipment listed on page 32 for the Marshall apparatus. It should again be noted that the maximum specific gravity tests were conducted using the mechanical shaker as described on page 33 of this thesis. AASHTO test T 269-90 describes only the procedure for determining air voids and is not a separate test. It uses the results of AASHTO tests T 166-88 and T 209-90 to calculate air voids.

TABLE 6. Asphalt Concrete Specimen Tests.

REQUIRED VALUE	AASHTO TEST CONDUCTED	AASHTO TEST #
Marshall Stability	Resistance to Plastic Flow Using Marshall Apparatus	T 245-90
Marshall Flow	Resistance to Plastic Flow Using Marshall Apparatus	T 245-90
Bulk Specific Gravity	Bulk Specific Gravity Using Saturated Surface-Dry Specimens	T 166-88
Density	Bulk Specific Gravity Using Saturated Surface-Dry Specimens	T 166-88
Max Specific Gravity	Maximum Specific Gravity of Bituminous Paving Mixtures	T 209-90
Percent Air Voids	Percent Air Voids in Compacted Dense Bituminous Mixtures	T 269-90

The primary parameters for determining if the tested specimens were prepared properly were the values obtained from AASHTO test T 209-90 and T 245-90. Under section nine (Precision) of AASHTO test T 209-90, the

maximum specific gravity test results of the three samples prepared with the exact same mixture combination should not have a range of values in excess of 0.011. If this range is exceeded, then the sample is considered improperly prepared and must be repeated. There are no parameters listed under AASHTO test T 245-90; however, for purposes of this investigation, if the standard deviation of the three like samples exceeded 1000 lbs, the sample was repeated. Likewise, if bulk specific gravities varied greatly, the sample was considered for rejection. Typically, if the maximum specific gravities were within range, the other values were also acceptable.

Schedule of Tests Conducted

Asphalt Tests

Prior to preparing asphalt pavement specimens, several tests were conducted on the asphalt alone to insure that the asphalt characteristics were consistent with those used in phase I and phase II. The asphalt tests conducted are shown in Table 7.

TABLE 7. Quality Control Asphalt Tests Conducted.

AASHTO TEST #	TEST DESCRIPTION
T49 - 80	Penetration of Bituminous Material
T53 - 81	Softening Point of Asphalt (Bitumen) and Tar in Ethylene Glycol (Ring & Ball)
T201-80	Kinematic Viscosity of Asphalt at 275°F
T179 -80	Effect of Heat and Air on Asphalt Materials (Thin Film Oven Test)

The asphalt tests were conducted on unmodified and modified samples

of both Conoco and Cenex asphalt. The number of tests conducted is shown in Table 8.

TABLE 8. Number of Asphalt Tests Conducted.

Asphalt Tests	Unmodified		Kraton Modified		Polybilt Modified	
	Cenex	Conoco	Cenex	Conoco	Cenex	Conoco
Penetration 39.2°F	9	9	9	9	9	9
Penetration @ 77°F	9	9	9	9	9	9
Softening Point	2	2	2	2	2	2
Viscosity	2	2	2	2	2	2
Thin Film Oven Test	4	4	4	4	4	4
AFTER TFOT	Cenex	Conoco	Cenex	Conoco	Cenex	Conoco
Penetration 39.2°F	9	9	9	9	9	9
Penetration @ 77°F	9	9	9	9	9	9
Softening Point	2	2	2	2	2	2
Viscosity	2	2	2	2	2	2

The results of these tests and those conducted during phases I and II are contained in reference [21]. The comparison of these results with the results from phase I and II indicate that the asphalts used in phase III are within the same range as those used in the earlier phases. Therefore, the asphalt concrete specimens prepared with asphalt in phase III can be compared directly with the specimens prepared during phase II.

Asphalt Concrete Specimen Tests

Test specimens were prepared using unmodified and modified Conoco and Cenex asphalt. These specimens were prepared at four different asphalt contents with two separate gradations for both phase II aggregate and

phase III aggregate.

During phase II, the samples prepared with phase II aggregate were compacted with the Marshall hammer only. These specimens were then tested and the results were published in the phase II report [11], and are included in this thesis.

During the current phase III, samples prepared with phase III aggregate were compacted with both the Marshall hammer and kneading compactor, and then were tested. Additionally, samples prepared with phase II aggregate and compacted with the kneading compactor were made to complete the required data needed for a comparative analysis of the two compactors. Table 9 lists the total number of samples prepared with the Marshall hammer and tested. This table also shows during which phase the samples were prepared and tested.

TABLE 9. Tests Conducted on Asphalt Specimens Compacted with the Marshall Hammer.

Asphalt Specimen Tests	Unmodified		Kraton Modified		Polybilt Modified	
	Cenex	Conoco	Cenex	Conoco	Cenex	Conoco
Specimens Prepared with Phase II Aggregates During Phase II						
Specimen Prep	24	24	24	24	24	24
Bulk Spec Gravity	24	24	24	24	24	24
Stability	24	24	24	24	24	24
Max Spec Gravity	24	24	24	24	24	24
Specimens Prepared with Phase III Aggregates During Phase III						
Specimen Prep	24	24	24	24	24	24
Bulk Spec Gravity	24	24	24	24	24	24
Stability	24	24	24	24	24	24
Max Spec Gravity	24	24	24	24	24	24

Table 10 lists the number of samples prepared with the kneading compactor. All specimens compacted with the kneading compactor were prepared and tested during phase III.

TABLE 10. Tests Conducted on Asphalt Specimens Compacted with the Kneading Compactor.

Asphalt Specimen Tests	Unmodified		Kraton Modified		Polybilt Modified	
	Cenex	Conoco	Cenex	Conoco	Cenex	Conoco
Specimens Prepared with Phase II Aggregates						
Specimen Prep	24	24	24	24	24	24
Bulk Spec Gravity	24	24	24	24	24	24
Stability	24	24	24	24	24	24
Max Spec Gravity	24	24	24	24	24	24
Specimens Prepared with Phase III Aggregates						
Specimen Prep	24	24	24	24	24	24
Bulk Spec Gravity	24	24	24	24	24	24
Stability	24	24	24	24	24	24
Max Spec Gravity	24	24	24	24	24	24

In summary, 576 asphalt test specimens were prepared and 1728 tests conducted on those specimens. Additionally, 288 asphalt tests were conducted prior to preparation of the asphalt specimens. The laboratory work commenced in October of 1991 and was completed in January of 1993.

Method of Data Analysis

The stated hypothesis for this thesis is to determine if there is a significant difference in the sensitivity to aggregate shape between the standard Marshall hammer and the California kneading compactor. To evaluate whether there is a significant difference, a statistical analysis

to determine inferences concerning two means is conducted.

The percentage increase in stability using angular aggregate (phase III aggregate) over semi-angular aggregate (phase II aggregate) for each compactor is calculated. For example, given the stability values for specimens prepared with the Marshall hammer for specimens containing phase II and phase III aggregates with 3.5% Conoco unmodified asphalt, the percent increase in stability can be calculated as shown below:

Marshall Stability - Phase II Aggregates = 5000 lbs
Marshall Stability - Phase III Aggregates = 5600 lbs

$$\% \text{ Increase} = \frac{\text{Phase III} - \text{Phase II}}{\text{Phase II}} \times 100 \text{ Equation (1)}$$

Using the given values with equation (1), the % increase is calculated:

$$\frac{5600 - 5000}{5000} \times 100 = 12\%$$

The individual values of percent increase in stability are then used to represent a sample population of data points for each compactor. For each of these sample populations, a mean and variance is calculated. Given the two sets of means and variances, inferences concerning the two means can be evaluated. From reference [22], the statistic for a test concerning the difference between two means with more than 30 data points is calculated using the following equation:

$$Z = \frac{(x_1 - x_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \text{ Equation (2)}$$

Where:

μ_1 - Population Mean of % Increase for Kneading Compactor

μ_2 - Population Mean of % Increase for Marshall Hammer

σ_1^2 - Kneading Compactor Population Variance

σ_2^2 - Marshall Hammer Population Variance

n_1 - Sample Size of Kneading Compactor Data

n_2 - Sample Size of Marshall Hammer Data

x_1 - Kneading Compactor Sample Mean

x_2 - Marshall Hammer Sample Mean

H_0 - Null Hypothesis

H_1 - Alternative Hypothesis

α - Level of Significance

Chapter seven, section nine of reference [22] outlines the procedure for rejecting or accepting a null hypothesis using two means. This procedure is summarized as follows:

1. State Null Hypothesis: $H_0 - \mu_1 - \mu_2 = 0$
Thus Alternative Hypothesis: $H_1 - \mu_1 - \mu_2 > 0$
2. Level of Significance: $\alpha = .05$
3. Criterion: Reject the null hypothesis if $Z > 1.645$
where Z is given by equation (2) where the value 1.645 represents the 95% level on a standard normal distribution table [22]

When the number of data points is less than 30, the sample variances can be calculated but the population variances are unknown. Therefore, either a sample "t" test or alternative sample "t" test is conducted. The "t" test statistic for a sample "t" test is calculated using equation (3):

$$t_{\alpha/2} = \frac{(x_1 - x_2) - (\mu_1 - \mu_2)}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}; v = n_1 + n_2 - 2$$

Equation (3)

$$\text{Where: } S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 - 1 + n_2 - 1}$$

When:

$$\sigma_1^2 = \sigma_2^2$$

And:

S_1^2 - Kneading Compactor Sample Variance

S_2^2 - Marshall Hammer Sample Variance

v - degree of freedom

The degree of freedom term is needed when using statistical Table 4 in reference [22] to correlate the calculated value of "t" with the prescribed level of significance. In the case where:

$$\sigma_1^2 \neq \sigma_2^2$$

Then equation (4) must be used to calculate the alternative test statistic "t":

$$t_{\alpha/2} = \frac{(x_1 - x_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}; \quad v = \left(\frac{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}{\frac{(\frac{S_1^2}{n_1})^2}{n_1 - 1} + \frac{(\frac{S_2^2}{n_2})^2}{n_2 - 1}} \right) - 2 \quad \text{Equation (4)}$$

Since the population variances are unknown, an additional statistical test, known as the "F" test is used to determine whether equation (3) or equation (4) is used. The "F" test statistic is calculated using equation (5):

$$F = \frac{S_1^2}{S_2^2}; \quad v_1 = (n_1 - 1) \quad v_2 = (n_2 - 1) \quad \text{Equation (5)}$$

Where: v_1, v_2 are degrees of freedom

If the "F" statistic is outside the level of significance as defined in Table 6(a) and 6(b) of reference [22], then the population variances are significantly different and equation (4) is used to calculate the "t" test statistic. If the variances are not significantly different then equation (3) is used.

The null hypothesis, if accepted, means that there is not a significant difference between the two population means. If the null hypothesis is rejected, the difference is significant.

To further illustrate this statistical analysis, consider Figure 18. The bell curves for both populations under consideration are superimposed upon each other. The null hypothesis is accepted in this case since the mean of the second population is within the interior 95% of the first population bell curve.

In Figure 19, the null hypothesis is rejected because the mean of the second population is outside the 95% probability area or

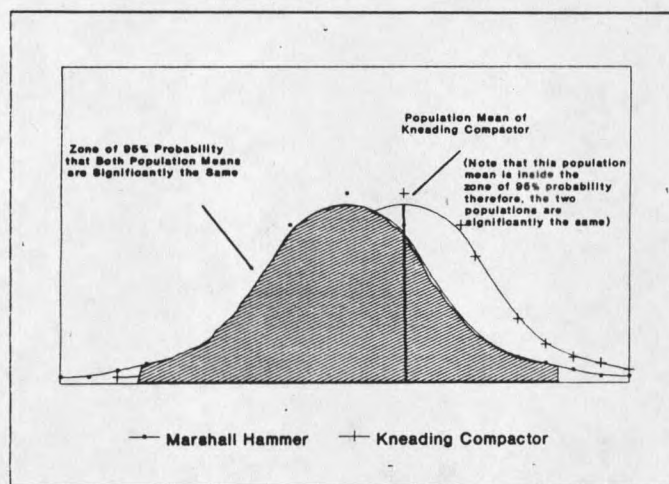


Figure 18. Accept Null Hypothesis.

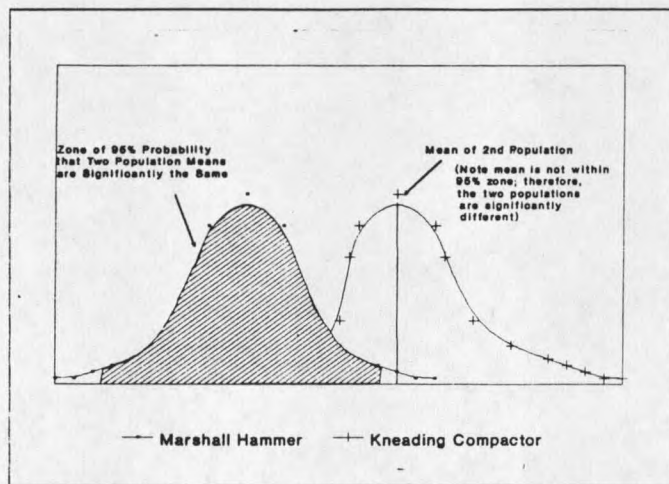


Figure 19. Reject Null Hypothesis.

is within the upper 2.5% (" $t_{\alpha/2}$ ") reach of the first population's bell curve. In this case the difference between the two population means is significantly different based on a level of significance of 5%. Additionally, the criterion for accepting or rejecting the null hypothesis at a level of significance of 5% when using either the "t" test or alternative "t" test is determined based on the calculated value of "t" and the degree of freedom used in conjunction with Table 4 in reference [22].

CHAPTER 5

OBSERVATIONS AND RESULTS OF STATISTICAL ANALYSIS

General ObservationsAppearance

The appearance of specimens prepared with the kneading compactor and the Marshall hammer differ in many respects. Shown in Figure 20, is a sample compacted with the kneading compactor. The top side of all samples exhibit a thin smooth surface of pure asphalt. This is primarily due to

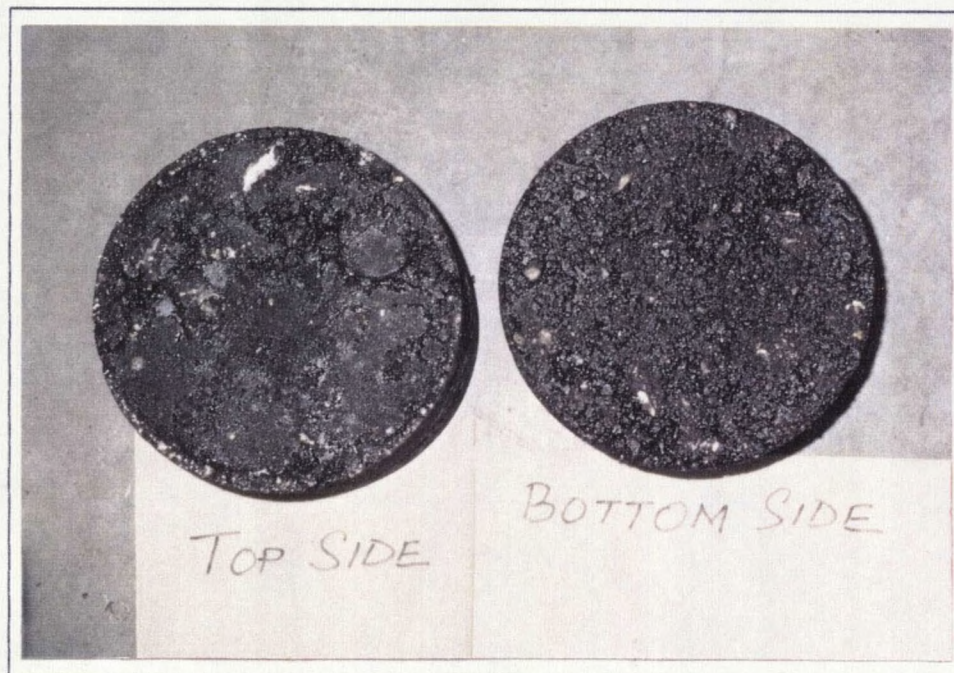


Figure 20. Top and Bottom Sides of Specimen Prepared with Kneading Compactor.

the heated tamping foot on the kneading compactor which serves the purpose of preventing asphalt from sticking to the foot. The heated foot tends to cause some asphalt to bleed to the surface. The top and bottom of Marshall specimens look identical to the bottom side of the kneading compactor sample in Figure 20. Figure 21 shows the side view of two specimens prepared with the kneading compactor. This figure illustrates a tendency for honeycombing on the lower half of the specimen. Marshall specimens also exhibit this honeycombing, but is equally likely to occur

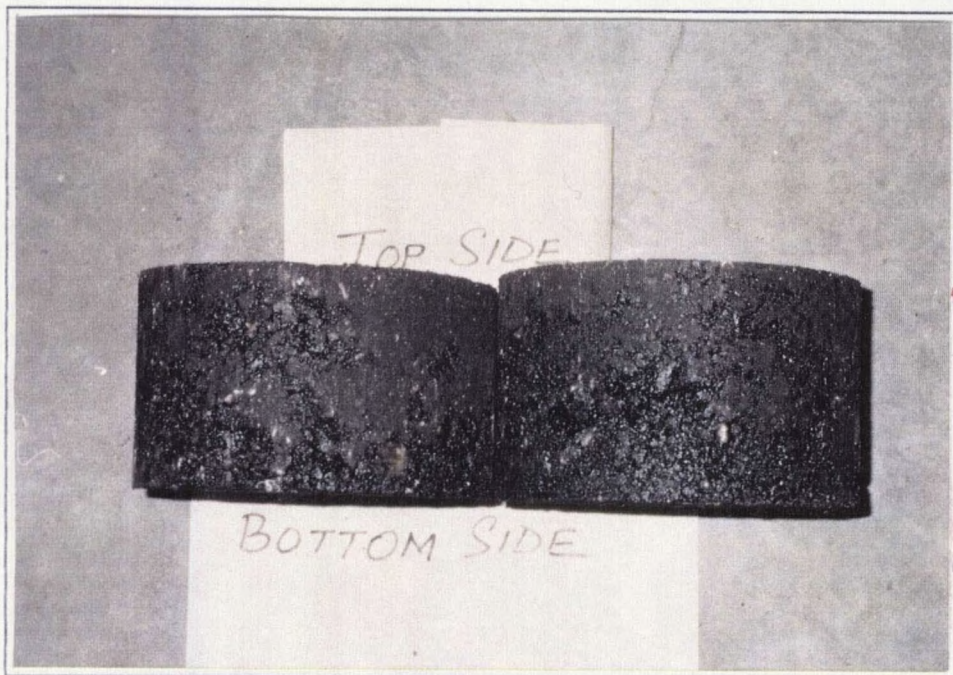


Figure 21. Side View of Samples Prepared with the Kneading Compactor.

on either the upper half or lower half. Aggregate breakage was observed to be much less in those samples prepared with the kneading compactor. Only in cases where large stone aggregates were situated at the very top of the mixture where the kneading foot made direct contact, did breakage

seem to occur. The Marshall hammer frequently exhibited aggregate breakage throughout the specimen.

Preparation Time

Initially the time to prepare specimens with the kneading compactor was much greater than that required with the Marshall hammer. Only six specimens compacted with the kneading compactor were prepared in a day versus 16 to 18 specimens with the Marshall hammer. However, after it was found that Marshall molds could be used with the kneading compactor and the technicians became more proficient, the same number of specimens were produced in a day by both compactors.

Stability

Referring to the stability curves (See Appendix A), it is apparent that the data generated by the kneading compactor produced curves which were more distinct than the data generated by the Marshall hammer. In many cases, the curve fitting for the Marshall data was an approximation at best.

For each asphalt content designated, three specimens were prepared, and the average stabilities of the three specimens were used as the stability for that specific asphalt content. The standard deviations for these averages were then calculated (See Appendix B). Throughout the testing process the samples prepared with the kneading compactor produced average stabilities with lower standard deviations. Exact data on the number of repeats was not maintained, so no statistical analysis can be performed to strengthen this observation. However, in general, the number of repeats required was relatively similar between the two compactors.

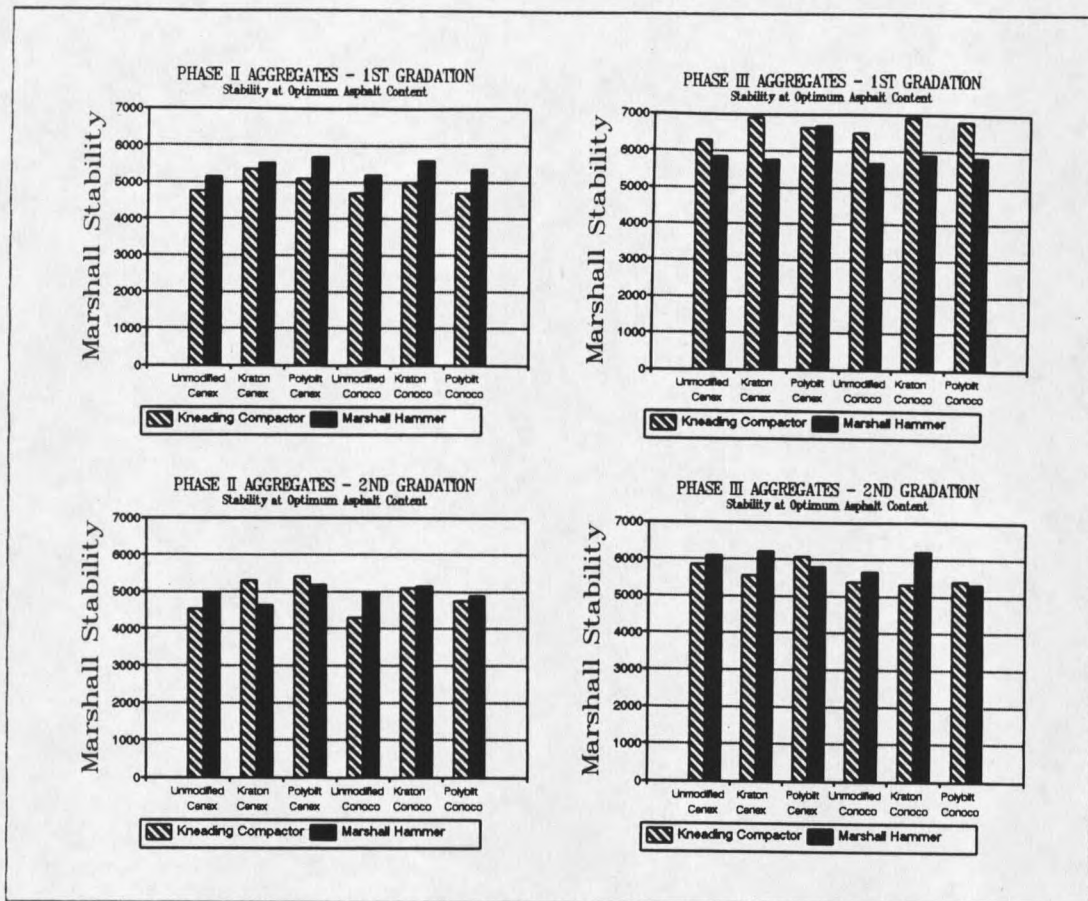


Figure 22. Marshall Stabilities at Optimum Asphalt Content.

This seems to indicate a potential for more consistent results with the kneading compactor.

Optimum asphalt contents were calculated from the Marshall test data and the properties at the optimum asphalt content were derived (See Appendix C). Figure 22 graphically shows the stability values at optimum asphalt content. Of particular interest, is the difference in stabilities between phase II aggregates and phase III aggregates for the first gradation (dense). The Marshall hammer produced higher stabilities for all asphalts with phase II aggregates. Whereas, the kneading compactor produced higher stabilities for specimens with phase III aggregates. The second gradation (less dense) data does not exhibit this same trend.

Density and Air Voids

Figure 23 shows that specimens produced with the kneading compactor

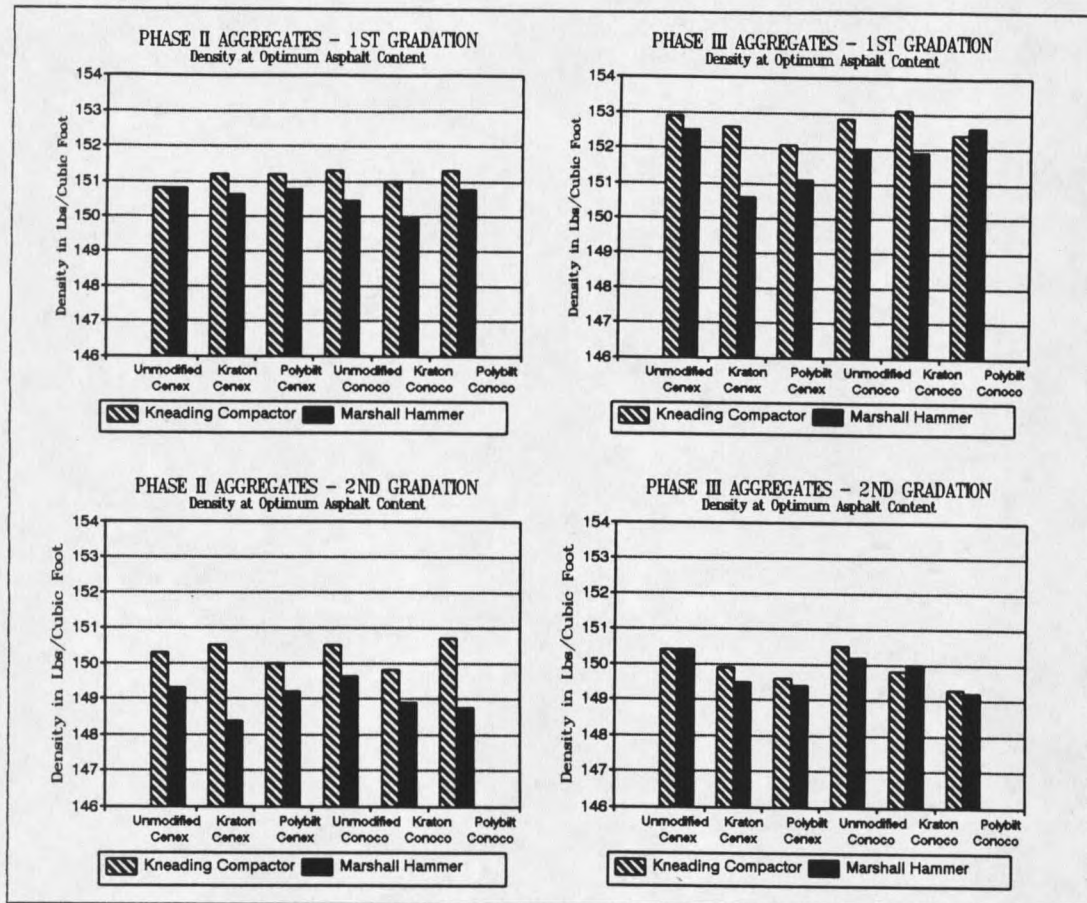


Figure 23. Densities at Optimum Asphalt Content.

exhibited higher densities than those prepared with the Marshall hammer. This difference appears to be significant in all cases except for those using phase III aggregates with the second gradation. But even in this case the kneading compactor densities are typically higher.

The air voids tended to be higher with first gradation specimens prepared with the Marshall hammer. This follows, since the densities are higher with the kneading compactor. However, with the second gradation, phase II aggregate specimens, the kneading compactor produced specimens

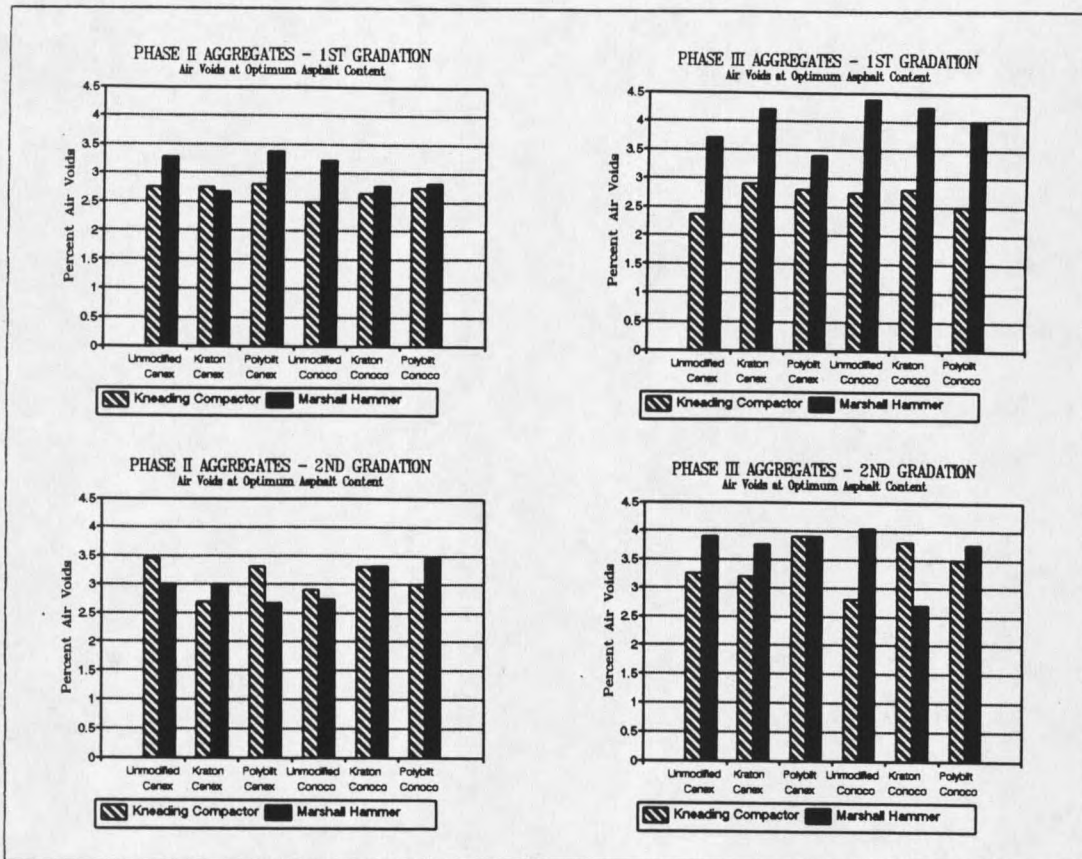


Figure 24. Air Voids at Optimum Asphalt Content.

with greater air voids in many cases (See Figure 24).

Results of Statistical Analysis

A statistical analysis using the inferences of two means as outlined in chapter four of this thesis was used to determine if there is a significant difference in aggregate shape sensitivity between the kneading compactor and Marshall hammer. The statistical analysis was applied to each subgroup of modified and unmodified asphalts and for each gradation. The analysis was then completed by comparing the entire set of data for each compactor.

For each of the subgroups, the number of samples was less than 30, so

the "t" test approach was used. When the entire set of data was analyzed, there were 48 data points in the sample and the "Z" test was used. The sample mean and sample standard deviation for each subgroup and entire data set were initially calculated (See Appendix D). These values were then used in the statistical equations.

Table 11 shows the results of the "F" tests conducted on the subgroup samples for the first gradation. In all cases except the polybilt modified asphalts, the test indicated that the population variances were significantly the same. Therefore, equation (3) was used to calculate the

TABLE 11. First Gradation "F" Test.

Asphalt Subgroup	Kneading Variance	Marshall Variance	"F"	v_1	v_2	Table "F"	t Test Eq.
Unmodified	60.09	104.44	1.74	7.0	7.0	3.79	Eq. (3)
Kraton Modified	73.62	122.10	1.66	7.0	7.0	3.79	Eq. (3)
Polybilt Modified	331.24	70.00	4.73	7.0	7.0	3.79	Eq. (4)
First Gradation	168.74	118.81	1.42	23	23	2.03	Eq. (3)

TABLE 12. First Gradation "t" Test.

Asphalt Subgroup	Kneading Mean	Marshall Mean	S_p^2	"t"	v	Table "t"	Accept H_0
Unmodified	30.66	10.22	86.8	.47	14	2.145	YES
Kraton Modified	29.89	11.05	97.9	.39	14	2.145	YES
Polybilt Modified	37.18	13.81	N/A	.20	7.8	2.355	YES
First Gradation	32.58	10.90	144	.52	46	1.960	YES

"t" statistic for all of the subgroups except for polybilt modified sample where equation (4) was used. Table 12 summarizes the "t" tests conducted for first gradation subgroup samples. In all cases the null hypothesis was accepted, which infers that there is not a significant difference.

The same analysis approach used for the first gradation subgroups was done for the second gradation subgroups. The results for the second gradation are shown in Tables 13 and 14. The "F" test indicated that the

TABLE 13. Second Gradation "F" Test.

Asphalt Subgroup	Kneading Variance	Marshall Variance	"F"	v_1	v_2	Table "F"	t Test Eq.
Unmodified	70.22	543.82	7.83	7.0	7.0	3.79	Eq. (4)
Kraton Modified	95.65	128.37	1.34	7.0	7.0	3.79	Eq. (3)
Polybilt Modified	242.74	52.13	4.66	7.0	7.0	3.79	Eq. (4)
Second Gradation	176.89	370.18	2.09	23	23	2.03	Eq. (4)

TABLE 14. Second Gradation "t" Test.

Asphalt Subgroup	Kneading Mean	Marshall Mean	S_p^2	"t"	v	Table "t"	Accept H_0
Unmodified	25.80	36.40	N/A	-.05	6.8	2.429	YES
Kraton Modified	12.40	24.62	112	-.22	14	2.145	YES
Polybilt Modified	24.87	8.71	N/A	.18	7.9	2.357	YES
Second Gradation	20.94	23.24	N/A	-.04	39	1.960	YES

population variances were significantly different for all subgroups except the kraton modified. Therefore, equation (4) was used for the unmodified,

polybilt modified and second gradation subgroups and equation (3) was used for the kraton modified. Again, in all cases the null hypothesis was accepted, indicating no significant difference.

Finally, when all of the data was considered as a whole, 48 data points for the kneading compactor and 48 data points for the Marshall hammer were used for the analysis. Therefore, equation (2) was used to calculate the "Z" statistic. Table 15 shows the results of the analysis.

Table 15. Entire Sample Set "Z" Test.

Test	Kneading Mean	Marshall Mean	"Z"	Table "Z" Value	Accept H_0
"Z" Test	26.76	16.37	3.31	1.65	NO

When all of the data is considered as a whole, the statistical analysis indicates that there is a significant difference between the two compactors. This analysis indicates the kneading compactor is more sensitive than the Marshall hammer when all samples are considered.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Discussion

Stability

Prior to the initiation of any tests, the investigator expected the kneading compactor to produce specimens with higher stabilities than the Marshall hammer. In fact, this is not the case. The kneading compactor specimens did exhibit higher stabilities when prepared with angular aggregates in a dense gradation. In contrast, the Marshall hammer produced specimens with higher stabilities when less angular aggregates were used with the same dense gradation. When a less dense gradation was used with either the angular or less angular aggregates, neither compactor consistently outperformed the other.

The results using a dense gradation with angular aggregates are of no surprise. In dense samples, there is very little room for the neighboring aggregates to move relative to each other. In addition, more work is needed to move angular aggregates past one another. The kneading compactor's ability to work the sample through the kneading process enables it to more effectively induce the dense angular aggregate into a strong interlocking configuration.

Less angular aggregates used with the same dense gradation produced results that were initially somewhat puzzling. After much thought, the

investigator proposes the following mechanistic explanation for this phenomenon. Less angular aggregates have many rounded faces, so when they are compacted with the kneading compactor they move past one another as expected. However, due to their round surfaces they continually move past one another without achieving good aggregate interlock. The Marshall hammer forces the aggregate into direct contact through impact blows, creating relative aggregate interlock relationships. This aggregate interlock is not the most optimum available, but is stronger than the less angular specimens prepared by the kneading compactor that apparently do not achieve good aggregate interlock. In some cases the Marshall hammer tends to cause aggregate breakage when compacting specimens. This breakage causes the aggregate to become much more angular, thus increasing the potential for stronger aggregate interlock relationships to occur. Therefore, in isolated cases, the Marshall hammer specimens exhibit higher stabilities due to aggregate breakage.

No trends resulted for either compactor when both angular and less angular aggregates were used in a less dense gradation. A less dense gradation allows more room for the aggregates to move during the compaction process. Therefore, less work or manipulation is needed to produce good angular interlock. This lends itself to the idea that the Marshall hammer is as likely to produce specimens with strong aggregate interlock as those made by the kneading compactor. In addition, aggregate breakage with less angular aggregates may cause increased stabilities for those specimens produced with the Marshall hammer.

Density and Air Voids

As expected, the density was consistently higher for specimens

produced with the kneading compactor for both gradations. The kneading compactor specimen air voids were also consistently lower except for those specimens made with less angular aggregates in a less dense gradation. This follows, since the kneading compactor works the sample so the aggregate and asphalt tend to fill most of the available void space. However, samples made with semi-angular aggregates in the less dense gradation showed no trends for either compactor. Often, the kneading compactor specimens had more air voids than Marshall hammer specimens. One possible explanation for this phenomenon is associated with the kneading compactor's ability to achieve tight aggregate interlock quickly with angular aggregates in a loose gradation. Simply put, less dense gradations initially have large voids present when the compaction process begins. If tight angular interlock relationships are developed early in the compaction process, asphalt is prevented from entering some of the void spaces, thus resulting in higher air void content. These early aggregate interlock relationships may not occur for every specimen. This may explain the lack of any trend with the less dense angular aggregates.

Any attempt to draw direct correlations between the two compactors is hampered by the large variation in results based on aggregate shape and gradation. Wood attempted to make correlations between the two compactors in 1971 [17], but found the same problems. He initially tried to correlate the two compactors using density, but found that increasing and decreasing the blows and tamps used by each compactor did not result in the consistent raising or lowering of specimen density. He did draw a correlation using stability, but this correlation was only valid for the materials he used. The same situation is present in this investigation.

The general correlations described above are limited to the specific asphalt, aggregate source, aggregate shape, and aggregate gradation used.

Statistical Analysis

The final decision to include the evaluation of the kneading compactor as part of Montana State University's Phase III research was made after the schedule and composition of tests were determined. These tests were developed to achieve the common research objectives agreed to by Montana State University, University of California - Berkeley, Montana Department of Transportation, and California Department of Transportation. Therefore, the evaluation of the kneading compactor had to be designed utilizing the existing schedule of tests. Additional testing was very limited due to time and financial constraints.

The stated hypothesis for this thesis was to determine if the kneading compactor was more sensitive to aggregate shape than the Marshall hammer. The statistical analysis of the data was conducted for each sample set (subgroup) of data categorized by asphalt type and gradation. The final part of the analysis included evaluating all of the data as a whole (entire set). If, in any of the analyses, the test null hypothesis is rejected, the kneading compactor is determined to be statistically more sensitive to aggregate shape with a level of significance of 5%.

For all of the subgroups, the null hypothesis was accepted, indicating no significant difference. When comparing this to the bar charts in Figure 22 on page 56, it appears that the analysis should have at least indicated a significant difference for the first gradation. The "t" test is extremely sensitive to sample variation. The "t" test evaluates small samples and, to be accurate, the small samples should

represent the overall population. Thus, the sample variance should be small. In all of the subgroups the variance was large. This is to be expected when using Marshall testing methods. Therefore, the results of the subgroup "t" tests do not provide inferences that represent the overall population.

The "Z" test uses many data points, and as such, the sample variance is considered to approximate the overall population variance. This means that the "Z" test is not as sensitive to large variances and should provide a useable inference concerning significant differences. The "Z" test analysis on the entire sample set resulted in the null hypothesis being rejected. Thus, this analysis indicates the kneading compactor is more sensitive to aggregate shape. However, this test alone is not conclusive. The data points used in the "Z" test were taken from the smaller samples and bias may have been introduced. Therefore, the statistical analysis only indicates that the kneading compactor is potentially more sensitive to aggregate shape than the Marshall hammer. To conclusively evaluate this sensitivity, additional research must be done.

Because of the large variation in Marshall data, any future research should include at least 30 data points for each sample set to eliminate possible bias. In each of these sample sets the asphalt percentage, asphalt type, source of aggregate, and aggregate gradation should remain constant. Only the aggregate shape should vary.

Conclusions

The kneading compactor and the Marshall hammer are the two most

common laboratory compactors used in the United States. Both have proven themselves in field use, resulting in many properly constructed roads. Comparison of laboratory compactors has been going on for decades. There is currently no consensus on which compactor is the best for use in hot asphalt mix design. Each compactor works through a different mechanism and it is up to the mix designer to understand how each compactor works. The designer must then become educated on how to interpret the results provided by each compactor.

The mobilization of the California kneading compactor and the guide included in chapter 3 of this thesis, provides the Montana Department of Transportation (MDT) with the ability to efficiently operate and maintain this versatile and advanced piece of testing equipment. Additionally, the acquisition of the kneading compactor demonstrates MDT's aggressive approach in evaluating new and different methods in asphalt mix design. The kneading compactor will benefit future efforts in both asphalt design and research.

The kneading compactor has many advantages. The compactor reduces aggregate breakage, tends to produce more consistent results, and most researchers agree it better simulates actual field compaction. When using dense gradations and angular aggregates, the kneading compactor seems to be very effective at optimizing aggregate to aggregate interlock. Disadvantages include the kneading compactor's high cost, and its large size. Because of its size, it is not portable and this seriously limits its role in field quality control applications.

The question as to which compactor provides better results for analyzing the improved benefits of angular large-stone in asphalt mix

design is only partially answered in this investigation. The statistical data indicates that the kneading compactor demonstrates a strong potential for improving aggregate interlock relationships, thus better demonstrates the potential benefits of the angular aggregate shape.

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REFERENCES CITED

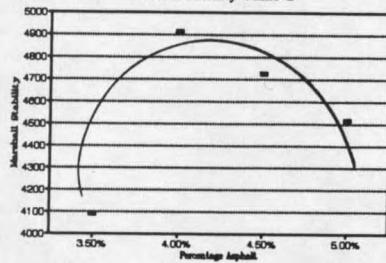
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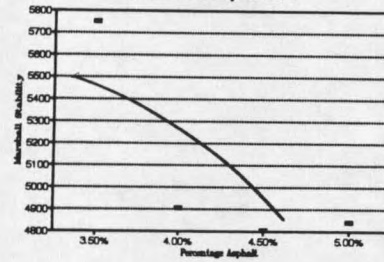
APPENDICES

APPENDIX A
STABILITY CURVES

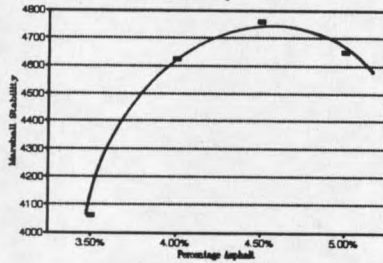
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Marshall Stability-Phase II



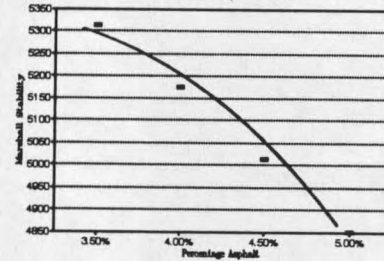
Unmodified Cenex - Marshall Hammer
Marshall Stability-Phase II



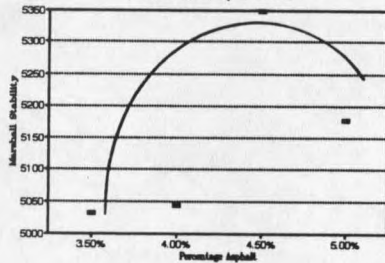
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Marshall Stability-Phase II



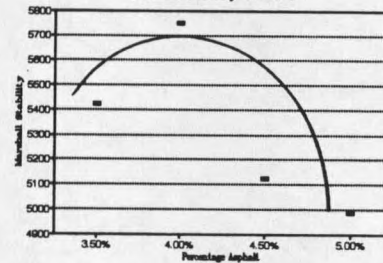
Unmodified Conoco - Marshall Hammer
Marshall Stability-Phase II



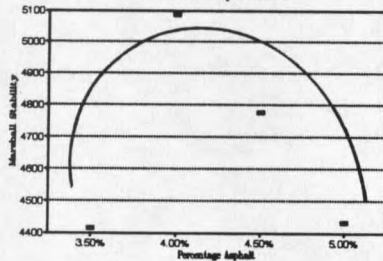
Kraton Cenex - Kneading Compactor
Marshall Stability-Phase II



Kraton Cenex - Marshall Hammer
Marshall Stability-Phase II



Kraton Conoco - Kneading Compactor
Marshall Stability-Phase II



Kraton Conoco - Marshall Hammer
Marshall Stability-Phase II

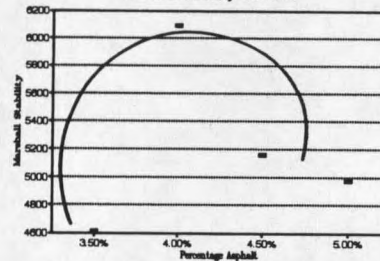


FIGURE 25. Stability Curves - 1st Gradation - Phase II Aggregates.

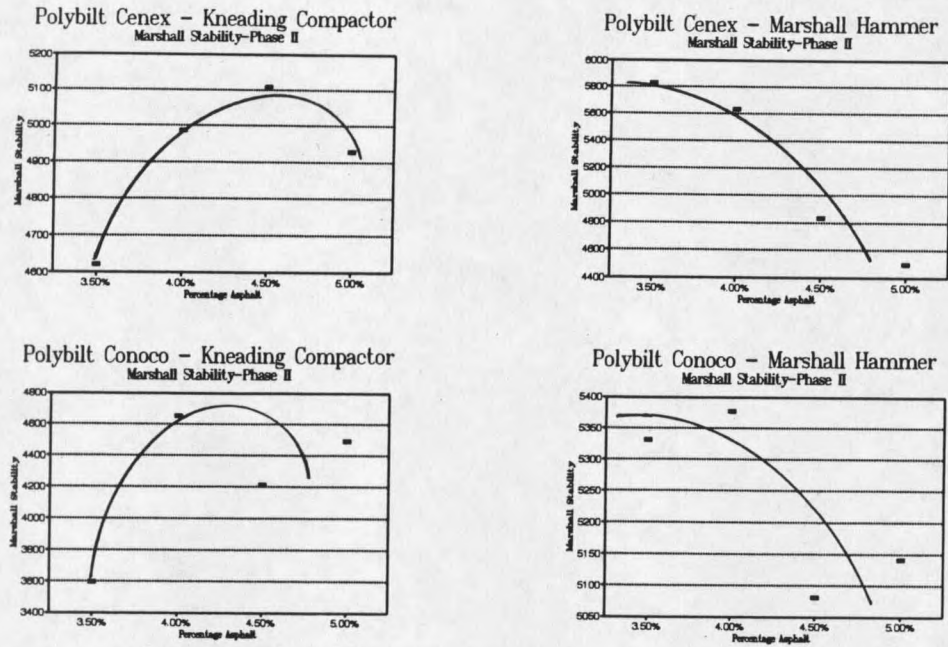


Figure 26. Stability Curves - 1st Gradation - Phase II Aggregates.

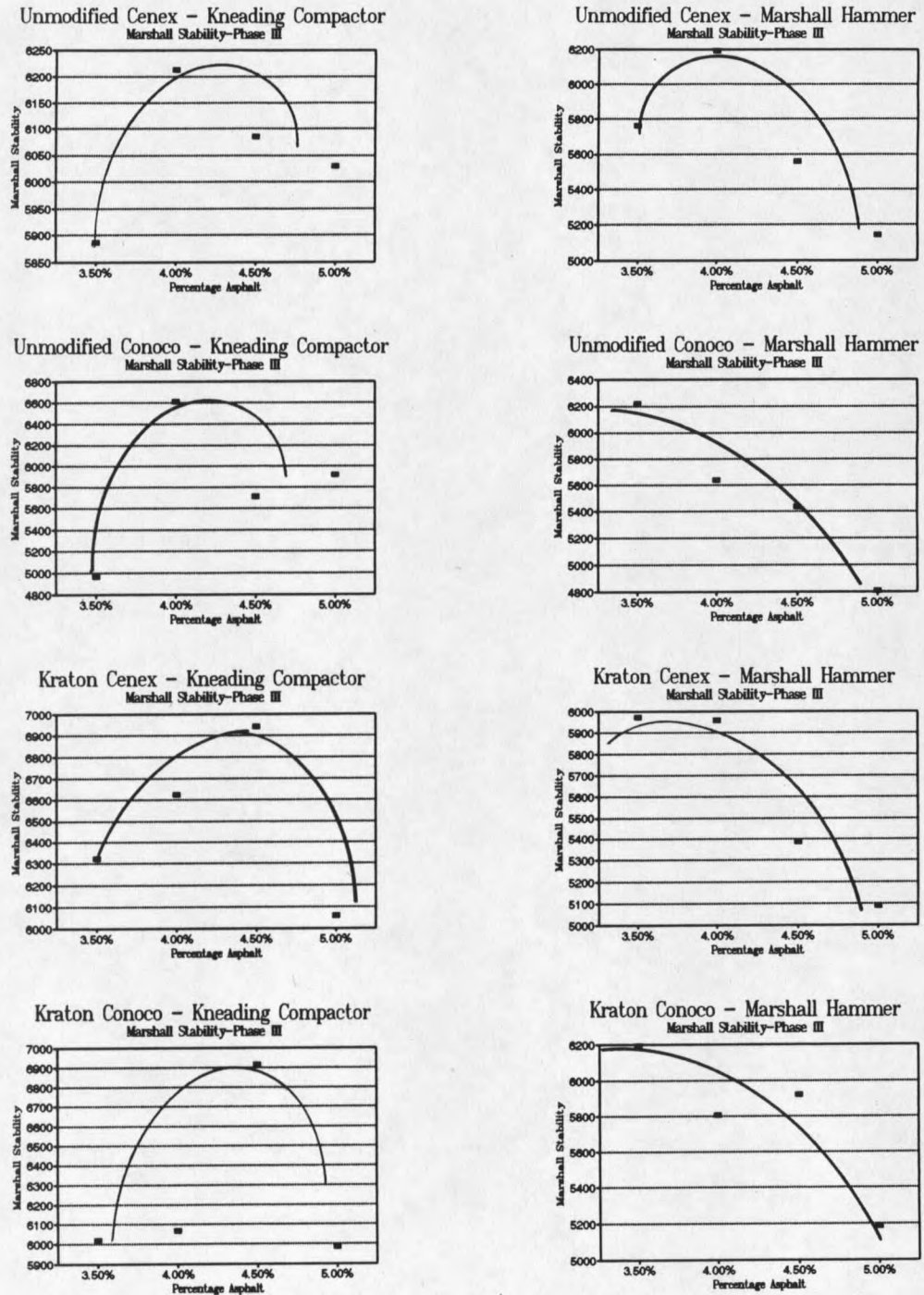


FIGURE 27. Stability Curves - 1st Gradation - Phase III Aggregates.

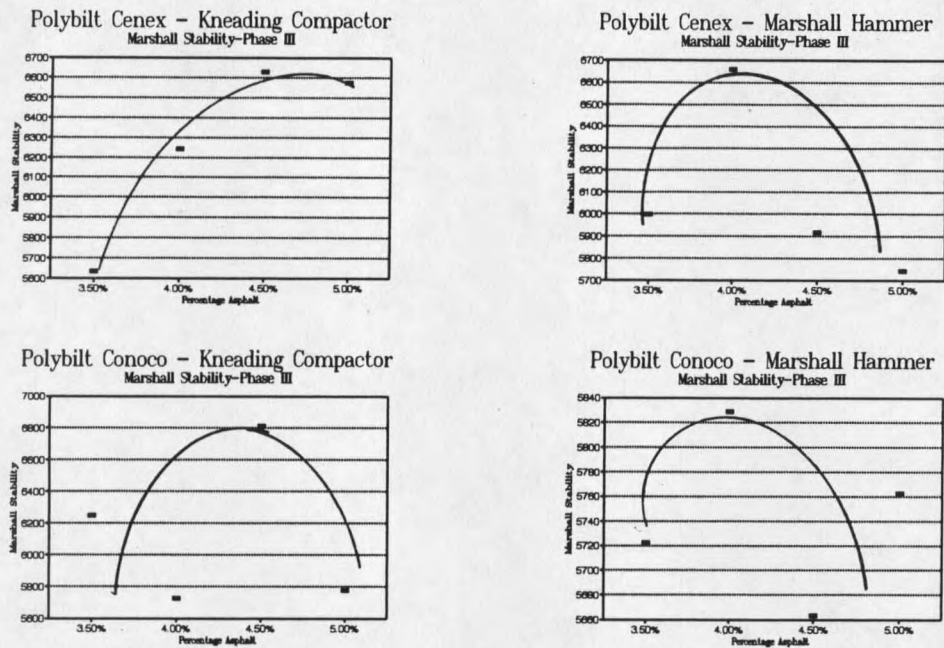
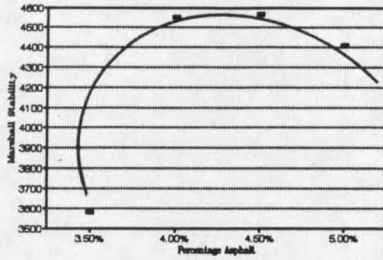
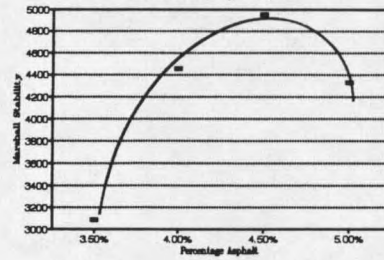


FIGURE 28. Stability Curves - 1st Gradation - Phase III Aggregates.

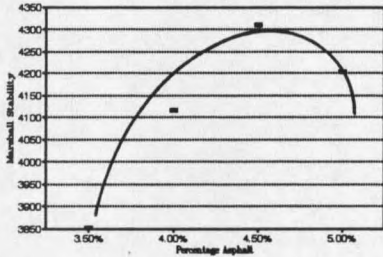
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Marshall Stability-Phase II



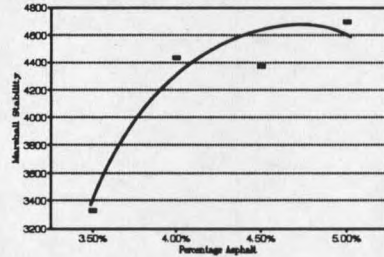
Unmodified Cenex - Marshall Hammer
Marshall Stability-Phase II



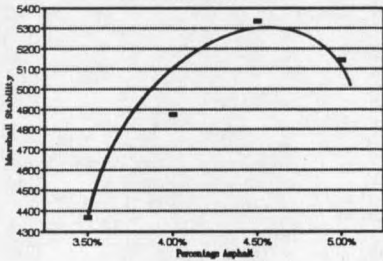
Unmodified Conoco - Kneading Compactor
Marshall Stability-Phase II



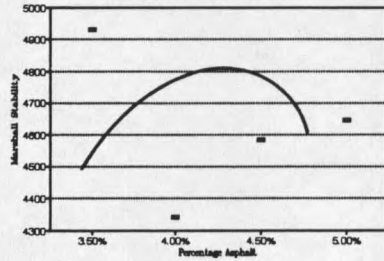
Unmodified Conoco - Marshall Hammer
Marshall Stability-Phase II



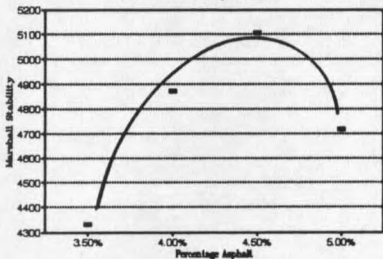
Kraton Cenex - Kneading Compactor
Marshall Stability-Phase II



Kraton Cenex - Marshall Hammer
Marshall Stability-Phase II



Kraton Conoco - Kneading Compactor
Marshall Stability-Phase II



Kraton Conoco - Marshall Hammer
Marshall Stability-Phase II

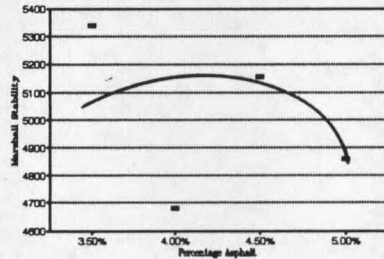


FIGURE 29. Stability Curves - 2nd Gradation - Phase II Aggregates.

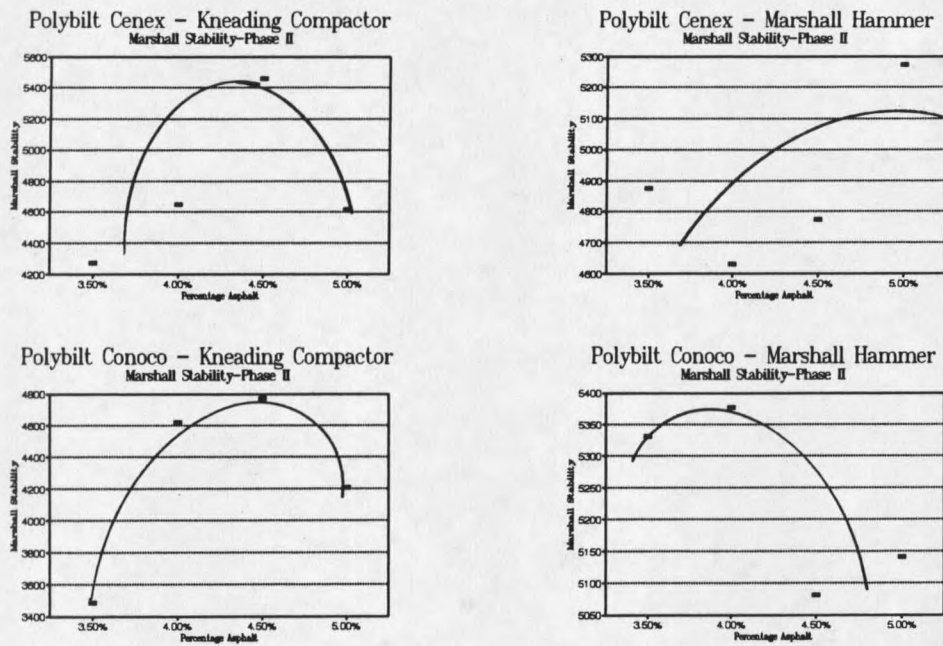
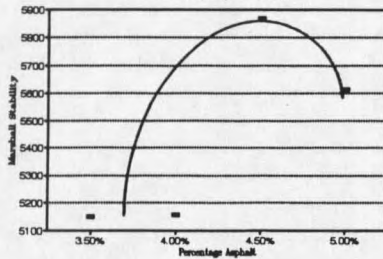
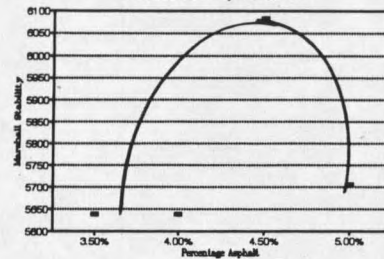


FIGURE 30. Stability Curves - 2nd Gradation - Phase II Aggregates.

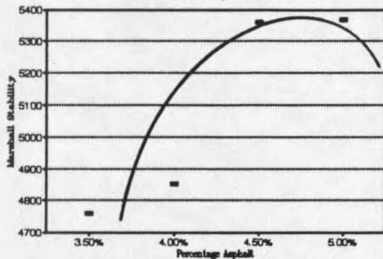
Unmodified Cenex - Kneading Compactor
Marshall Stability-Phase III



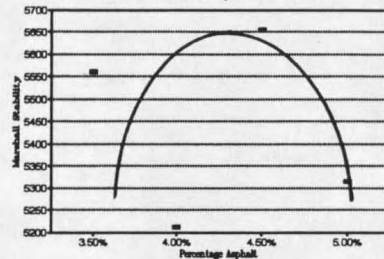
Unmodified Cenex - Marshall Hammer
Marshall Stability-Phase III



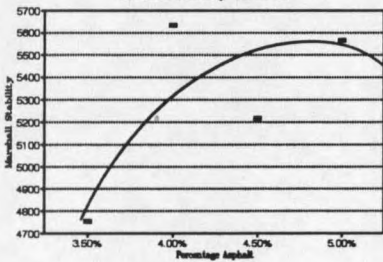
Unmodified Conoco - Kneading Compactor
Marshall Stability-Phase III



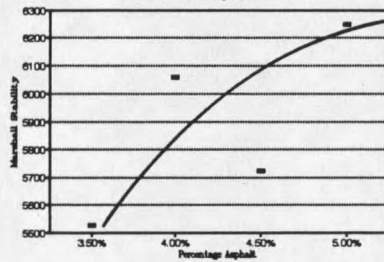
Unmodified Conoco - Marshall Hammer
Marshall Stability-Phase III



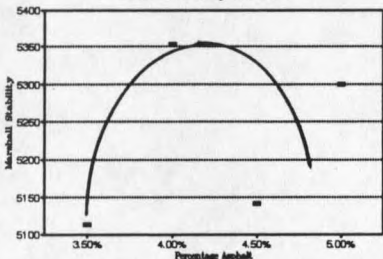
Kraton Cenex - Kneading Compactor
Marshall Stability-Phase III



Kraton Cenex - Marshall Hammer
Marshall Stability-Phase III



Kraton Conoco - Kneading Compactor
Marshall Stability-Phase III



Kraton Conoco - Marshall Hammer
Marshall Stability-Phase III

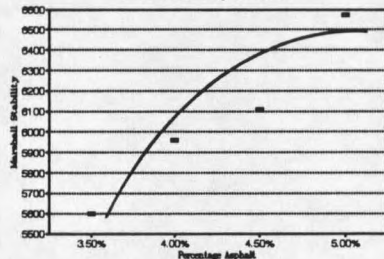


FIGURE 31. Stability Curves - 2nd Gradation - Phase III Aggregates.

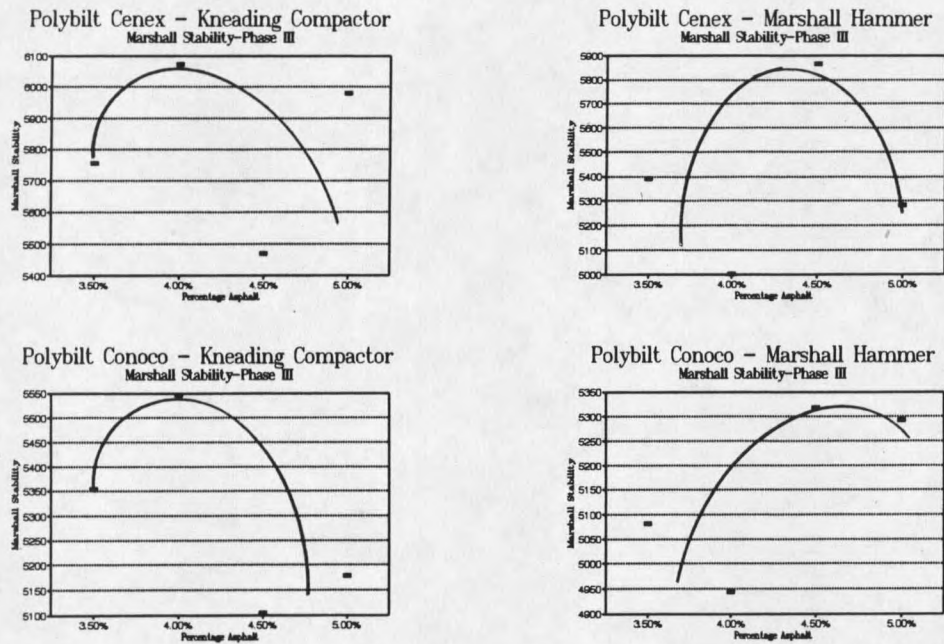


FIGURE 32. Stability Curves - 2nd Gradation - Phase III Aggregates.

APPENDIX B

MARSHALL TEST RESULTS

TABLE 16.
UNMODIFIED KNEADING COMPACTOR - 1ST GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	5886.00	6213.50	6085.33	6029.33
Standard Dev. Marshall Stability	335.96	203.79	216.08	69.84
Mean Marshall Flow in 1/100 inch.	22.00	22.67	28.33	24.00
Standard Deviation Marshall Flow	4.08	2.05	2.87	1.41
Mean Bulk Specific Gravity	2.415	2.438	2.453	2.482
Standard Deviation Bulk Sp. Gr.	0.000	0.007	0.018	0.004
Unit Weight in Pcf.	150.67	152.13	153.09	154.90
Mean Rice Specific Gravity	2.558	2.535	2.519	2.507
Standard Deviation Rice Sp. Gr.	0.0049	0.005	0.004	0.004
Mean Percent Air Voids	5.62	3.86	2.61	1.00
Standard Deviation % Air Voids	0.18	0.20	0.86	0.20
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	4968.50	6612.67	5712.00	5917.33
Standard Dev. Marshall Stability	151.53	179.84	45.72	424.85
Mean Marshall Flow in 1/100 inch.	20.00	27.00	23.33	24.33
Standard Deviation Marshall Flow	2.45	1.41	1.25	2.05
Mean Bulk Specific Gravity	2.409	2.398	2.453	2.464
Standard Deviation Bulk Sp. Gr.	0.009	0.045	0.009	0.006
Unit Weight in Pcf.	150.34	149.66	153.06	153.77
Mean Rice Specific Gravity	2.5603	2.514	2.520	2.510
Standard Deviation Rice Sp. Gr.	0.00492	0.005	0.003	0.004
Mean Percent Air Voids	5.90	4.59	2.67	1.82
Standard Deviation % Air Voids	0.41	1.58	0.25	0.37

TABLE 17.
UNMODIFIED KNEADING COMPACTOR - 1ST GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	4090.83	4911.00	4723.33	4515.17
Standard Dev. Marshall Stability	424.48	382.99	370.53	358.72
Mean Marshall Flow in 1/100 inch.	21.67	19.33	19.00	21.00
Standard Deviation Marshall Flow	4.50	2.05	0.82	0.82
Mean Bulk Specific Gravity	2.375	2.394	2.411	2.421
Standard Deviation Bulk Sp. Gr.	0.016	0.018	0.007	0.011
Unit Weight in Pcf.	148.18	149.39	150.43	151.09
Mean Rice Specific Gravity	2.534	2.514	2.489	2.479
Standard Deviation Rice Sp. Gr.	0.0008	0.006	0.004	0.006
Mean Percent Air Voids	6.29	4.77	3.15	2.34
Standard Deviation % Air Voids	0.61	0.92	0.25	0.61
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	4063.33	4623.33	4759.67	4650.67
Standard Dev. Marshall Stability	411.30	194.31	256.92	51.38
Mean Marshall Flow in 1/100 inch.	19.00	17.67	20.00	20.33
Standard Deviation Marshall Flow	1.63	1.89	1.41	1.25
Mean Bulk Specific Gravity	2.365	2.400	2.426	2.415
Standard Deviation Bulk Sp. Gr.	0.011	0.012	0.006	0.004
Unit Weight in Pcf.	147.58	149.74	151.40	150.70
Mean Rice Specific Gravity	2.525	2.503	2.481	2.468
Standard Deviation Rice Sp. Gr.	0.004	0.003	0.003	0.004
Mean Percent Air Voids	6.35	4.12	2.19	2.13
Standard Deviation % Air Voids	0.50	0.40	0.19	0.15

TABLE 18.

KRATON MODIFIED KNEADING COMPACTOR - 1ST GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	6322.00	6623.50	6942.17	6057.33
Standard Dev. Marshall Stability	177.99	254.37	546.66	397.52
Mean Marshall Flow in 1/100 inch.	23.00	28.67	29.00	27.00
Standard Deviation Marshall Flow	0.82	3.09	1.41	1.41
Mean Bulk Specific Gravity	2.403	2.429	2.440	2.453
Standard Deviation Bulk Sp. Gr.	0.011	0.017	0.021	0.008
Unit Weight in Pcf.	149.93	151.57	152.15	153.05
Mean Rice Specific Gravity	2.56	2.540	2.510	2.512
Standard Deviation Rice Sp. Gr.	0.0004	0.005	0.006	0.001
Mean Percent Air Voids	6.16	4.36	2.95	2.36
Standard Deviation % Air Voids	0.44	0.60	0.61	0.27
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	6018.50	6065.67	6917.33	5986.50
Standard Dev. Marshall Stability	340.36	414.50	41.48	667.63
Mean Marshall Flow in 1/100 inch.	25.00	26.67	27.67	29.00
Standard Deviation Marshall Flow	1.41	4.99	2.62	2.94
Mean Bulk Specific Gravity	2.400	2.428	2.456	2.446
Standard Deviation Bulk Sp. Gr.	0.018	0.019	0.008	0.024
Unit Weight in Pcf.	149.76	151.49	153.25	152.63
Mean Rice Specific Gravity	2.56	2.536	2.520	2.500
Standard Deviation Rice Sp. Gr.	0.004	0.002	0.003	0.003
Mean Percent Air Voids	6.16	4.28	2.57	2.29
Standard Deviation % Air Voids	0.81	0.69	0.18	1.03

TABLE 19.

KRATON MODIFIED KNEADING COMPACTOR - 1ST GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	5032.17	5044.67	5348.50	5177.50
Standard Dev. Marshall Stability	156.28	496.90	534.30	160.44
Mean Marshall Flow in 1/100 inch.	22.67	22.00	24.00	28.67
Standard Deviation Marshall Flow	0.47	0.00	2.16	2.46
Mean Bulk Specific Gravity	2.404	2.392	2.421	2.433
Standard Deviation Bulk Sp. Gr.	0.006	0.007	0.014	0.011
Unit Weight in Pcf.	150.00	149.24	151.07	151.82
Mean Rice Specific Gravity	2.524	2.507	2.483	2.461
Standard Deviation Rice Sp. Gr.	0.005	0.001	0.005	0.003
Mean Percent Air Voids	4.74	4.61	2.51	1.15
Standard Deviation % Air Voids	0.40	0.31	0.69	0.38
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	4414.50	5086.67	4777.83	4432.67
Standard Dev. Marshall Stability	160.44	597.60	334.00	328.01
Mean Marshall Flow in 1/100 inch.	20.67	24.50	19.33	28.67
Standard Deviation Marshall Flow	1.70	3.50	3.68	3.30
Mean Bulk Specific Gravity	2.392	2.409	2.427	2.429
Standard Deviation Bulk Sp. Gr.	0.017	0.003	0.004	0.005
Unit Weight in Pcf.	149.28	150.32	151.42	151.55
Mean Rice Specific Gravity	2.518	2.494	2.477	2.486
Standard Deviation Rice Sp. Gr.	0.004	0.005	0.006	0.004
Mean Percent Air Voids	5.00	3.42	2.37	2.30
Standard Deviation % Air Voids	0.34	0.10	1.98	0.75

TABLE 20.**POLYBILT MODIFIED KNEADING COMPACTOR - 1ST GRADATION - ANGULAR**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	5634.67	6241.67	6630.08	6574.83
Standard Dev. Marshall Stability	678.95	734.21	210.29	456.63
Mean Marshall Flow in 1/100 inch.	20.33	22.67	24.33	29.00
Standard Deviation Marshall Flow	0.47	4.03	4.20	4.08
Mean Bulk Specific Gravity	2.374	2.407	2.439	2.433
Standard Deviation Bulk Sp. Gr.	0.014	0.028	0.007	0.010
Unit Weight in Pcf.	148.16	150.19	152.17	151.82
Mean Rice Specific Gravity	2.536	2.510	2.509	2.489
Standard Deviation Rice Sp. Gr.	0.0042	0.005	0.006	0.001
Mean Percent Air Voids	6.39	4.11	2.79	2.25
Standard Deviation % Air Voids	0.45	1.02	0.35	0.39
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	6248.70	5724.50	6813.33	5779.00
Standard Dev. Marshall Stability	517.36	567.56	653.60	473.57
Mean Marshall Flow in 1/100 inch.	22.67	25.00	23.33	30.00
Standard Deviation Marshall Flow	3.68	6.98	1.25	2.83
Mean Bulk Specific Gravity	2.376	2.407	2.449	2.423
Standard Deviation Bulk Sp. Gr.	0.012	0.018	0.008	0.022
Unit Weight in Pcf.	148.24	150.19	152.84	151.17
Mean Rice Specific Gravity	2.538	2.530	2.505	2.473
Standard Deviation Rice Sp. Gr.	0.002	0.005	0.006	0.004
Mean Percent Air Voids	6.38	4.71	2.22	2.02
Standard Deviation % Air Voids	0.40	0.53	0.27	0.79

TABLE 21.**POLYBILT MODIFIED KNEADING COMPACTOR - 1ST GRADATION - ROUND**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	4620.00	4986.17	5108.50	4927.83
Standard Dev. Marshall Stability	74.22	102.59	394.56	310.63
Mean Marshall Flow in 1/100 inch.	17.33	18.67	20.67	20.33
Standard Deviation Marshall Flow	0.94	1.25	4.78	3.30
Mean Bulk Specific Gravity	2.407	2.408	2.423	2.440
Standard Deviation Bulk Sp. Gr.	0.006	0.011	0.017	0.002
Unit Weight in Pcf.	150.18	150.26	151.17	152.21
Mean Rice Specific Gravity	2.519	2.508	2.492	2.476
Standard Deviation Rice Sp. Gr.	0.003	0.000	0.005	0.002
Mean Percent Air Voids	4.47	4.00	2.78	1.49
Standard Deviation % Air Voids	0.11	0.46	0.85	0.17
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	3597.00	4650.67	4214.67	4492.33
Standard Dev. Marshall Stability	320.89	210.29	289.53	248.23
Mean Marshall Flow in 1/100 inch.	19.33	17.67	22.67	19.67
Standard Deviation Marshall Flow	0.47	3.09	0.94	1.89
Mean Bulk Specific Gravity	2.393	2.413	2.418	2.437
Standard Deviation Bulk Sp. Gr.	0.008	0.013	0.012	0.002
Unit Weight in Pcf.	149.32	150.55	150.90	152.10
Mean Rice Specific Gravity	2.521	2.511	2.500	2.478
Standard Deviation Rice Sp. Gr.	0.002	0.001	0.003	0.003
Mean Percent Air Voids	5.08	3.92	3.28	1.65
Standard Deviation % Air Voids	0.24	0.49	0.59	0.06

TABLE 22.

UNMODIFIED KNEADING COMPACTOR - 2ND GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	5150.00	5158.67	5866.83	5613.50
Standard Dev. Marshall Stability	366.58	392.66	307.37	117.73
Mean Marshall Flow in 1/100 inch.	20.00	23.00	19.33	23.00
Standard Deviation Marshall Flow	2.16	2.49	0.47	0.82
Mean Bulk Specific Gravity	2.353	2.373	2.403	2.440
Standard Deviation Bulk Sp. Gr.	0.006	0.011	0.005	0.005
Unit Weight in Pcf.	146.85	148.05	149.97	152.28
Mean Rice Specific Gravity	2.533	2.513	2.502	2.488
Standard Deviation Rice Sp. Gr.	0.0056	0.004	0.004	0.005
Mean Percent Air Voids	7.09	5.57	3.94	1.93
Standard Deviation % Air Voids	0.25	0.34	0.34	0.00
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	4757.33	4852.33	5360.67	5367.67
Standard Dev. Marshall Stability	107.94	196.22	564.14	203.25
Mean Marshall Flow in 1/100 inch.	18.67	21.67	21.67	22.00
Standard Deviation Marshall Flow	1.70	0.94	1.55	1.00
Mean Bulk Specific Gravity	2.362	2.368	2.413	2.421
Standard Deviation Bulk Sp. Gr.	0.018	0.021	0.002	0.017
Unit Weight in Pcf.	147.41	147.78	150.55	151.09
Mean Rice Specific Gravity	2.546	2.507	2.492	2.476
Standard Deviation Rice Sp. Gr.	0.0029	0.004	0.004	0.005
Mean Percent Air Voids	7.20	5.53	3.20	2.21
Standard Deviation % Air Voids	0.61	0.92	0.13	0.56

TABLE 23.

UNMODIFIED KNEADING COMPACTOR - 2ND GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	3581.83	4551.33	4566.17	4408.33
Standard Dev. Marshall Stability	145.08	181.32	125.85	112.22
Mean Marshall Flow in 1/100 inch.	17.67	17.00	18.00	18.00
Standard Deviation Marshall Flow	0.94	2.16	2.83	2.16
Mean Bulk Specific Gravity	2.345	2.373	2.404	2.420
Standard Deviation Bulk Sp. Gr.	0.006	0.024	0.003	0.008
Unit Weight in Pcf.	146.32	148.10	150.01	150.80
Mean Rice Specific Gravity	2.538	2.500	2.495	2.483
Standard Deviation Rice Sp. Gr.	0.0014	0.003	0.005	0.002
Mean Percent Air Voids	7.60	5.07	3.66	2.66
Standard Deviation % Air Voids	0.20	0.86	0.30	0.30
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	3851.33	4116.33	4310.67	4204.33
Standard Dev. Marshall Stability	330.51	307.01	264.40	288.58
Mean Marshall Flow in 1/100 inch.	17.67	15.67	17.00	16.33
Standard Deviation Marshall Flow	1.25	0.94	1.41	0.47
Mean Bulk Specific Gravity	2.364	2.391	2.411	2.412
Standard Deviation Bulk Sp. Gr.	0.004	0.006	0.010	0.010
Unit Weight in Pcf.	147.53	149.22	150.47	150.51
Mean Rice Specific Gravity	2.528	2.503	2.488	2.469
Standard Deviation Rice Sp. Gr.	0.003	0.006	0.001	0.002
Mean Percent Air Voids	6.49	4.45	3.09	2.32
Standard Deviation % Air Voids	0.19	0.40	0.34	0.36

TABLE 24.

KRATON MODIFIED KNEADING COMPACTOR - 2ND GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	4755.17	5633.67	5214.67	5565.00
Standard Dev. Marshall Stability	24.28	432.54	439.27	412.81
Mean Marshall Flow in 1/100 inch.	20.33	18.00	18.67	21.00
Standard Deviation Marshall Flow	0.47	0.00	1.88	2.16
Mean Bulk Specific Gravity	2.338	2.370	2.380	2.405
Standard Deviation Bulk Sp. Gr.	0.011	0.012	0.007	0.003
Unit Weight in Pcf.	145.87	147.90	148.51	150.09
Mean Rice Specific Gravity	2.535	2.515	2.495	2.468
Standard Deviation Rice Sp. Gr.	0.003	0.005	0.002	0.007
Mean Percent Air Voids	7.77	5.76	4.60	2.53
Standard Deviation % Air Voids	0.55	0.30	0.26	0.25
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	5113.17	5353.00	5141.00	5300.00
Standard Dev. Marshall Stability	581.96	228.99	337.98	384.63
Mean Marshall Flow in 1/100 inch.	20.67	20.00	19.67	20.00
Standard Deviation Marshall Flow	1.25	6.48	3.77	3.74
Mean Bulk Specific Gravity	2.363	2.384	2.393	2.412
Standard Deviation Bulk Sp. Gr.	0.003	0.001	0.012	0.003
Unit Weight in Pcf.	147.45	148.76	149.34	150.53
Mean Rice Specific Gravity	2.529	2.511	2.490	2.472
Standard Deviation Rice Sp. Gr.	0.003	0.000	0.004	0.005
Mean Percent Air Voids	6.56	5.07	3.88	2.41
Standard Deviation % Air Voids	0.16	0.05	0.55	0.31

TABLE 25.

KRATON MODIFIED KNEADING COMPACTOR - 2ND GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	4369.50	4876.00	5335.33	5144.00
Standard Dev. Marshall Stability	172.06	337.98	330.51	259.68
Mean Marshall Flow in 1/100 inch.	18.67	20.00	23.00	25.00
Standard Deviation Marshall Flow	0.94	0.00	0.82	0.00
Mean Bulk Specific Gravity	2.347	2.389	2.409	2.415
Standard Deviation Bulk Sp. Gr.	0.010	0.002	0.008	0.003
Unit Weight in Pcf.	146.47	149.09	150.30	150.70
Mean Rice Specific Gravity	2.549	2.514	2.485	2.466
Standard Deviation Rice Sp. Gr.	0.004	0.004	0.003	0.002
Mean Percent Air Voids	7.90	4.95	3.06	2.05
Standard Deviation % Air Voids	0.43	0.15	0.37	0.04
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	4329.83	4870.83	5105.67	4717.00
Standard Dev. Marshall Stability	177.69	495.00	281.56	263.23
Mean Marshall Flow in 1/100 inch.	21.00	22.67	23.67	25.33
Standard Deviation Marshall Flow	2.16	1.25	3.40	2.63
Mean Bulk Specific Gravity	2.385	2.381	2.393	2.409
Standard Deviation Bulk Sp. Gr.	0.006	0.014	0.008	0.003
Unit Weight in Pcf.	148.82	148.57	149.34	150.30
Mean Rice Specific Gravity	2.506	2.483	2.480	2.470
Standard Deviation Rice Sp. Gr.	0.001	0.006	0.001	0.005
Mean Percent Air Voids	4.83	4.10	3.48	2.50
Standard Deviation % Air Voids	0.22	0.45	0.30	0.31

TABLE 26.

POLYBILT MODIFIED KNEADING COMPACTOR - 2ND GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	5755.33	6072.33	5469.65	5978.33
Standard Dev. Marshall Stability	376.81	247.96	457.33	512.77
Mean Marshall Flow in 1/100 inch.	21.67	19.67	22.00	19.66
Standard Deviation Marshall Flow	2.05	2.49	2.94	2.06
Mean Bulk Specific Gravity	2.370	2.383	2.400	2.431
Standard Deviation Bulk Sp. Gr.	0.018	0.019	0.025	0.004
Unit Weight in Pcf.	147.97	148.72	149.78	151.69
Mean Rice Specific Gravity	2.54	2.518	2.507	2.496
Standard Deviation Rice Sp. Gr.	0.004	0.001	0.005	0.000
Mean Percent Air Voids	6.74	5.35	4.24	2.17
Standard Deviation % Air Voids	0.79	0.81	1.07	0.19
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	5353.00	5547.33	5103.67	5178.00
Standard Dev. Marshall Stability	439.19	347.10	406.25	406.72
Mean Marshall Flow in 1/100 inch.	22.00	23.33	23.33	24.00
Standard Deviation Marshall Flow	3.74	3.30	1.70	1.63
Mean Bulk Specific Gravity	2.383	2.390	2.390	2.401
Standard Deviation Bulk Sp. Gr.	0.005	0.008	0.001	0.029
Unit Weight in Pcf.	148.70	148.87	149.36	149.80
Mean Rice Specific Gravity	2.547	2.510	2.489	2.469
Standard Deviation Rice Sp. Gr.	0.0037	0.007	0.005	0.005
Mean Percent Air Voids	6.44	4.95	3.99	2.75
Standard Deviation % Air Voids	0.27	0.06	0.14	1.20

TABLE 27.

POLYBILT MODIFIED KNEADING COMPACTOR - 2ND GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	4272.17	4646.73	5459.00	4617.67
Standard Dev. Marshall Stability	242.33	277.62	129.82	628.10
Mean Marshall Flow in 1/100 inch.	18.67	21.33	22.33	24.30
Standard Deviation Marshall Flow	2.63	0.94	0.47	1.25
Mean Bulk Specific Gravity	2.368	2.381	2.399	2.418
Standard Deviation Bulk Sp. Gr.	0.012	0.014	0.007	0.005
Unit Weight in Pcf.	147.78	148.55	149.70	150.86
Mean Rice Specific Gravity	2.522	2.521	2.503	2.467
Standard Deviation Rice Sp. Gr.	0.001	0.001	0.005	0.003
Mean Percent Air Voids	6.09	5.58	4.15	1.99
Standard Deviation % Air Voids	0.46	0.56	0.48	0.12
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	3481.67	4619.50	4770.00	4208.33
Standard Dev. Marshall Stability	454.61	411.89	439.19	133.28
Mean Marshall Flow in 1/100 inch.	18.33	21.00	20.67	17.33
Standard Deviation Marshall Flow	2.05	1.41	3.30	0.94
Mean Bulk Specific Gravity	2.376	2.367	2.419	2.421
Standard Deviation Bulk Sp. Gr.	0.011	0.005	0.006	0.009
Unit Weight in Pcf.	148.24	147.72	150.97	151.05
Mean Rice Specific Gravity	2.521	2.516	2.494	2.470
Standard Deviation Rice Sp. Gr.	0.005	0.006	0.001	0.002
Mean Percent Air Voids	5.76	5.90	2.98	2.01
Standard Deviation % Air Voids	0.46	0.42	0.27	0.32

TABLE 28.**UNMODIFIED MARSHALL HAMMER (112 Blows) - 1ST GRADATION - ANGULAR**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	5761.67	6194.83	5555.50	5142.67
Standard Dev. Marshall Stability	322.27	226.90	710.82	905.72
Mean Marshall Flow in 1/100 inch.	15.17	16.33	15.17	17.33
Standard Deviation Marshall Flow	0.76	0.58	3.01	1.76
Mean Bulk Specific Gravity	2.423	2.422	2.447	2.464
Standard Deviation Bulk Sp. Gr.	0.008	0.012	0.019	0.008
Unit Weight in Pcf.	151.20	151.13	152.69	153.75
Mean Rice Specific Gravity	2.567	2.552	2.537	2.521
Standard Deviation Rice Sp. Gr.	0.014	0.007	0.006	0.011
Mean Percent Air Voids	5.76	5.07	3.54	2.28
Standard Deviation % Air Voids	0.22	0.27	0.67	0.56
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	6219.00	5635.97	5435.17	4804.67
Standard Dev. Marshall Stability	509.33	339.56	602.20	261.28
Mean Marshall Flow in 1/100 inch.	14.00	17.83	16.50	15.50
Standard Deviation Marshall Flow	1.73	3.33	1.80	3.28
Mean Bulk Specific Gravity	2.410	2.428	2.441	2.445
Standard Deviation Bulk Sp. Gr.	0.020	0.016	0.021	0.013
Unit Weight in Pcf.	150.38	151.51	152.32	152.57
Mean Rice Specific Gravity	2.559	2.545	2.534	2.497
Standard Deviation Rice Sp. Gr.	0.005	0.006	0.006	0.003
Mean Percent Air Voids	5.84	4.58	3.67	2.08
Standard Deviation % Air Voids	0.95	0.84	0.81	0.65

TABLE 29.**UNMODIFIED MARSHALL HAMMER (112 Blows) - 1ST GRADATION - ROUND**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	5749.75	4905.00	4805.10	4841.20
Standard Dev. Marshall Stability	401.42	196.50	103.17	122.88
Mean Marshall Flow in 1/100 inch.	12.00	12.33	12.67	14.33
Standard Deviation Marshall Flow	1.00	0.58	1.15	1.53
Mean Bulk Specific Gravity	2.401	2.407	2.425	2.428
Standard Deviation Bulk Sp. Gr.	0.006	0.005	0.010	0.007
Unit Weight in Pcf.	149.82	150.20	151.32	151.51
Mean Rice Specific Gravity	2.526	2.495	2.494	2.474
Standard Deviation Rice Sp. Gr.	0.009	0.004	0.011	0.008
Mean Percent Air Voids	4.95	3.51	2.79	1.89
Standard Deviation % Air Voids	0.21	0.06	0.65	0.44
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	5313.75	5175.00	5014.00	4850.50
Standard Dev. Marshall Stability	668.04	332.56	196.50	536.76
Mean Marshall Flow in 1/100 inch.	15.67	16.00	15.67	14.67
Standard Deviation Marshall Flow	3.06	2.00	2.52	1.15
Mean Bulk Specific Gravity	2.392	2.410	2.424	2.423
Standard Deviation Bulk Sp. Gr.	0.003	0.019	0.003	0.011
Unit Weight in Pcf.	149.26	150.38	151.26	151.20
Mean Rice Specific Gravity	2.51	2.487	2.481	2.457
Standard Deviation Rice Sp. Gr.	0.006	0.005	0.009	0.004
Mean Percent Air Voids	4.70	3.10	2.32	1.37
Standard Deviation % Air Voids	0.20	0.55	0.43	0.29

TABLE 30.**KRATON MODIFIED MARSHALL HAMMER (112 Blows) - 1ST GRADATION - ANGULAR**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	5971.02	5958.67	5386.83	5086.67
Standard Dev. Marshall Stability	544.88	834.28	999.48	582.75
Mean Marshall Flow in 1/100 inch.	17.00	20.00	27.33	20.33
Standard Deviation Marshall Flow	1.00	1.73	14.57	5.03
Mean Bulk Specific Gravity	2.385	2.422	2.414	2.440
Standard Deviation Bulk Sp. Gr.	0.016	0.008	0.016	0.006
Unit Weight in Pcf.	148.80	151.10	150.60	152.25
Mean Rice Specific Gravity	2.555	2.545	2.520	2.504
Standard Deviation Rice Sp. Gr.	0.001	0.007	0.003	0.001
Mean Percent Air Voids	6.68	4.87	4.21	2.57
Standard Deviation % Air Voids	0.57	0.01	0.59	0.17
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	6194.83	5804.67	5919.33	5184.67
Standard Dev. Marshall Stability	328.51	920.39	131.06	767.88
Mean Marshall Flow in 1/100 inch.	16.67	18.00	17.33	22.33
Standard Deviation Marshall Flow	1.15	1.73	2.31	1.53
Mean Bulk Specific Gravity	2.405	2.397	2.438	2.452
Standard Deviation Bulk Sp. Gr.	0.010	0.009	0.012	0.008
Unit Weight in Pcf.	150.10	149.57	152.11	152.98
Mean Rice Specific Gravity	2.56	2.530	2.520	2.510
Standard Deviation Rice Sp. Gr.	0.003	0.001	0.007	0.005
Mean Percent Air Voids	6.03	5.20	3.29	2.20
Standard Deviation % Air Voids	0.51	0.30	0.25	0.11

TABLE 31.**KRATON MODIFIED MARSHALL HAMMER (112 Blows) - 1ST GRADATION - ROUND**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	5423.67	5749.75	5123.00	4987.75
Standard Dev. Marshall Stability	509.30	374.60	237.60	419.50
Mean Marshall Flow in 1/100 inch.	15.00	14.00	18.33	18.67
Standard Deviation Marshall Flow	4.36	1.00	0.58	1.53
Mean Bulk Specific Gravity	2.377	2.411	2.416	2.417
Standard Deviation Bulk Sp. Gr.	0.002	0.004	0.003	0.005
Unit Weight in Pcf.	148.32	150.45	150.76	150.82
Mean Rice Specific Gravity	2.515	2.492	2.474	2.462
Standard Deviation Rice Sp. Gr.	0.009	0.009	0.006	0.003
Mean Percent Air Voids	5.49	3.35	2.35	1.80
Standard Deviation % Air Voids	0.26	0.41	0.16	0.10
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	4611.80	6092.42	5162.00	4973.70
Standard Dev. Marshall Stability	256.98	734.36	252.10	246.23
Mean Marshall Flow in 1/100 inch.	15.00	15.00	18.00	17.67
Standard Deviation Marshall Flow	1.00	2.00	2.00	2.52
Mean Bulk Specific Gravity	2.376	2.399	2.408	2.411
Standard Deviation Bulk Sp. Gr.	0.006	0.006	0.010	0.002
Unit Weight in Pcf.	148.26	149.70	150.26	150.45
Mean Rice Specific Gravity	2.502	2.480	2.468	2.446
Standard Deviation Rice Sp. Gr.	0.002	0.008	0.015	0.006
Mean Percent Air Voids	5.01	3.28	2.43	1.42
Standard Deviation % Air Voids	0.19	0.22	0.28	0.32

TABLE 32.

POLYBILT MODIFIED MARSHALL HAMMER (112 Blows) - 1ST GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	5996.50	6657.50	5916.83	5744.17
Standard Dev. Marshall Stability	342.16	354.66	417.50	665.21
Mean Marshall Flow in 1/100 inch.	16.00	16.00	19.33	17.33
Standard Deviation Marshall Flow	1.73	1.00	4.04	2.08
Mean Bulk Specific Gravity	2.412	2.431	2.448	2.447
Standard Deviation Bulk Sp. Gr.	0.004	0.016	0.007	0.018
Unit Weight in Pcf.	150.54	151.68	152.75	152.70
Mean Rice Specific Gravity	2.551	2.533	2.518	2.508
Standard Deviation Rice Sp. Gr.	0.002	0.018	0.006	0.006
Mean Percent Air Voids	5.42	4.04	2.78	2.42
Standard Deviation % Air Voids	0.15	0.13	0.11	0.77
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	5722.50	5829.00	5663.00	5762.33
Standard Dev. Marshall Stability	331.51	432.63	193.27	741.11
Mean Marshall Flow in 1/100 inch.	15.33	15.67	20.33	19.67
Standard Deviation Marshall Flow	2.52	0.58	3.21	3.06
Mean Bulk Specific Gravity	2.409	2.446	2.444	2.440
Standard Deviation Bulk Sp. Gr.	0.021	0.019	0.010	0.013
Unit Weight in Pcf.	150.31	152.62	152.53	152.25
Mean Rice Specific Gravity	2.57	2.543	2.522	2.487
Standard Deviation Rice Sp. Gr.	0.002	0.006	0.007	0.006
Mean Percent Air Voids	6.28	3.81	3.06	1.90
Standard Deviation % Air Voids	0.80	0.64	0.21	0.41

TABLE 33.

POLYBILT MODIFIED MARSHALL HAMMER (112 Blows) - 1ST GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	5831.50	5631.70	4832.30	4496.25
Standard Dev. Marshall Stability	54.50	300.20	309.90	401.40
Mean Marshall Flow in 1/100 inch.	15.33	13.33	14.67	19.33
Standard Deviation Marshall Flow	4.04	0.58	0.58	4.04
Mean Bulk Specific Gravity	2.391	2.418	2.423	2.415
Standard Deviation Bulk Sp. Gr.	0.010	0.006	0.010	0.009
Unit Weight in Pcf.	149.20	150.95	151.20	150.70
Mean Rice Specific Gravity	2.52	2.494	2.475	2.462
Standard Deviation Rice Sp. Gr.	0.003	0.004	0.006	0.008
Mean Percent Air Voids	5.11	3.02	2.09	1.91
Standard Deviation % Air Voids	0.33	0.35	0.17	0.47
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	5330.83	5377.30	5081.33	5141.17
Standard Dev. Marshall Stability	65.40	409.05	321.03	245.75
Mean Marshall Flow in 1/100 inch.	14.00	16.33	16.33	16.33
Standard Deviation Marshall Flow	2.00	2.30	0.58	1.53
Mean Bulk Specific Gravity	2.379	2.406	2.424	2.424
Standard Deviation Bulk Sp. Gr.	0.017	0.012	0.005	0.006
Unit Weight in Pcf.	148.45	150.13	151.26	151.26
Mean Rice Specific Gravity	2.513	2.485	2.469	2.455
Standard Deviation Rice Sp. Gr.	0.005	0.006	0.004	0.002
Mean Percent Air Voids	5.32	3.18	2.06	1.25
Standard Deviation % Air Voids	0.88	0.25	0.56	0.21

TABLE 34.
UNMODIFIED MARSHALL HAMMER (112 Blows) - 2ND GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	5639.67	5638.17	6082.33	5706.33
Standard Dev. Marshall Stability	475.23	386.43	246.24	344.84
Mean Marshall Flow in 1/100 inch.	14.67	17.33	15.67	16.33
Standard Deviation Marshall Flow	2.08	4.04	1.53	4.73
Mean Bulk Specific Gravity	2.363	2.372	2.410	2.397
Standard Deviation Bulk Sp. Gr.	0.013	0.027	0.009	0.010
Unit Weight in Pcf.	147.44	148.00	150.41	149.60
Mean Rice Specific Gravity	2.546	2.526	2.508	2.491
Standard Deviation Rice Sp. Gr.	0.006	0.004	0.004	0.005
Mean Percent Air Voids	7.20	6.09	3.91	3.76
Standard Deviation % Air Voids	0.41	1.18	0.23	0.29
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	5560.00	5211.67	5654.83	5313.67
Standard Dev. Marshall Stability	596.72	514.76	269.15	266.06
Mean Marshall Flow in 1/100 inch.	16.67	15.00	14.67	15.67
Standard Deviation Marshall Flow	3.06	2.65	2.08	1.53
Mean Bulk Specific Gravity	2.368	2.371	2.406	2.405
Standard Deviation Bulk Sp. Gr.	0.003	0.019	0.014	0.012
Unit Weight in Pcf.	147.75	147.94	150.12	150.10
Mean Rice Specific Gravity	2.549	2.511	2.515	2.488
Standard Deviation Rice Sp. Gr.	0.003	0.007	0.005	0.006
Mean Percent Air Voids	7.09	5.59	4.34	3.33
Standard Deviation % Air Voids	0.21	0.99	0.37	0.29

TABLE 35.
UNMODIFIED MARSHALL HAMMER (112 Blows) - 2ND GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Unmodified Cenex 120/150			
Mean Marshall Stability in lbs.	3082.17	4455.30	4949.92	4328.75
Standard Dev. Marshall Stability	453.06	205.00	164.87	296.44
Mean Marshall Flow in 1/100 inch.	12.67	11.00	13.33	15.00
Standard Deviation Marshall Flow	1.70	0.00	2.31	3.61
Mean Bulk Specific Gravity	2.310	2.360	2.389	2.403
Standard Deviation Bulk Sp. Gr.	0.013	0.008	0.004	0.016
Unit Weight in Pcf.	144.16	147.26	149.07	149.95
Mean Rice Specific Gravity	2.538	2.492	2.464	2.458
Standard Deviation Rice Sp. Gr.	0.003	0.017	0.014	0.006
Mean Percent Air Voids	8.97	5.27	3.06	2.62
Standard Deviation % Air Voids	0.61	0.37	0.52	0.06
Tests	Unmodified Conoco 120/150			
Mean Marshall Stability in lbs.	3330.33	4434.33	4373.20	4696.67
Standard Dev. Marshall Stability	667.96	214.20	476.70	396.54
Mean Marshall Flow in 1/100 inch.	13.67	12.67	12.67	14.33
Standard Deviation Marshall Flow	1.70	1.53	2.08	1.53
Mean Bulk Specific Gravity	2.317	2.364	2.383	2.395
Standard Deviation Bulk Sp. Gr.	0.006	0.010	0.016	0.014
Unit Weight in Pcf.	144.58	147.51	148.70	149.45
Mean Rice Specific Gravity	2.52	2.495	2.479	2.461
Standard Deviation Rice Sp. Gr.	0.002	0.012	0.009	0.009
Mean Percent Air Voids	8.06	5.24	3.87	2.58
Standard Deviation % Air Voids	0.27	0.12	0.29	0.21

TABLE 36.

KRATON MODIFIED MARSHALL HAMMER (112 Blows) - 2ND GRADATION - ANGULAR

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	5527.67	6059.83	5724.00	6248.67
Standard Dev. Marshall Stability	214.41	515.86	347.54	129.61
Mean Marshall Flow in 1/100 inch.	13.33	15.00	14.33	20.00
Standard Deviation Marshall Flow	2.08	1.73	3.06	3.00
Mean Bulk Specific Gravity	2.346	2.347	2.392	2.390
Standard Deviation Bulk Sp. Gr.	0.005	0.007	0.005	0.012
Unit Weight in Pcf.	146.39	146.45	149.23	149.15
Mean Rice Specific Gravity	2.534	2.513	2.500	2.472
Standard Deviation Rice Sp. Gr.	0.002	0.007	0.005	0.004
Mean Percent Air Voids	7.43	6.61	4.34	3.32
Standard Deviation % Air Voids	0.25	0.50	0.35	0.34
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	5597.33	5958.83	6108.67	6572.00
Standard Dev. Marshall Stability	867.19	714.32	244.79	265.00
Mean Marshall Flow in 1/100 inch.	15.67	16.00	18.00	20.33
Standard Deviation Marshall Flow	1.53	1.73	4.00	1.53
Mean Bulk Specific Gravity	2.334	2.369	2.387	2.414
Standard Deviation Bulk Sp. Gr.	0.029	0.021	0.011	0.005
Unit Weight in Pcf.	145.62	147.80	148.96	150.65
Mean Rice Specific Gravity	2.531	2.505	2.483	2.459
Standard Deviation Rice Sp. Gr.	0.002	0.006	0.002	0.002
Mean Percent Air Voids	7.79	5.46	3.84	1.83
Standard Deviation % Air Voids	1.08	0.63	0.46	0.15

TABLE 37.

KRATON MODIFIED MARSHALL HAMMER (112 Blows) - 2ND GRADATION - ROUND

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Kraton modified Cenex 120/150			
Mean Marshall Stability in lbs.	4930.83	4341.00	4583.50	4646.30
Standard Dev. Marshall Stability	27.10	181.20	97.20	150.70
Mean Marshall Flow in 1/100 inch.	10.67	13.67	15.00	15.33
Standard Deviation Marshall Flow	0.47	1.53	1.00	2.08
Mean Bulk Specific Gravity	2.322	2.342	2.363	2.380
Standard Deviation Bulk Sp. Gr.	0.010	0.014	0.006	0.005
Unit Weight in Pcf.	144.89	146.14	147.45	148.51
Mean Rice Specific Gravity	2.512	2.479	2.456	2.445
Standard Deviation Rice Sp. Gr.	0.004	0.006	0.002	0.006
Mean Percent Air Voids	7.56	5.52	3.79	2.67
Standard Deviation % Air Voids	0.28	0.47	0.25	0.16
Tests	Kraton modified Conoco 120/150			
Mean Marshall Stability in lbs.	5338.83	4681.67	5155.08	4858.30
Standard Dev. Marshall Stability	267.05	271.97	314.56	662.70
Mean Marshall Flow in 1/100 inch.	12.00	12.00	16.00	15.33
Standard Deviation Marshall Flow	0.81	1.00	2.00	0.58
Mean Bulk Specific Gravity	2.311	2.361	2.377	2.394
Standard Deviation Bulk Sp. Gr.	0.011	0.003	0.015	0.006
Unit Weight in Pcf.	144.22	147.33	148.32	149.39
Mean Rice Specific Gravity	2.515	2.483	2.462	2.453
Standard Deviation Rice Sp. Gr.	0.011	0.004	0.013	0.008
Mean Percent Air Voids	8.11	4.91	3.47	2.38
Standard Deviation % Air Voids	0.25	0.24	0.71	0.41

TABLE 38:**POLYBILT MODIFIED MARSHALL HAMMER (112 Blows) - 2ND GRADATION - ANGULAR**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	5390.33	5002.17	5865.33	5282.33
Standard Dev. Marshall Stability	610.08	596.16	186.13	30.60
Mean Marshall Flow in 1/100 inch.	14.00	18.67	13.67	17.67
Standard Deviation Marshall Flow	1.73	2.89	2.08	1.15
Mean Bulk Specific Gravity	2.355	2.364	2.388	2.404
Standard Deviation Bulk Sp. Gr.	0.011	0.009	0.007	0.006
Unit Weight in Pcf.	146.94	147.50	149.03	149.87
Mean Rice Specific Gravity	2.536	2.512	2.499	2.479
Standard Deviation Rice Sp. Gr.	0.002	0.005	0.003	0.007
Mean Percent Air Voids	7.14	5.90	4.43	3.13
Standard Deviation % Air Voids	0.38	0.49	0.37	0.45
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	5081.33	4944.00	5317.67	5292.33
Standard Dev. Marshall Stability	773.07	643.23	411.68	612.06
Mean Marshall Flow in 1/100 inch.	14.00	13.00	13.33	13.67
Standard Deviation Marshall Flow	5.29	1.00	3.06	3.51
Mean Bulk Specific Gravity	2.352	2.351	2.388	2.391
Standard Deviation Bulk Sp. Gr.	0.009	0.007	0.007	0.012
Unit Weight in Pcf.	146.75	146.71	149.02	149.18
Mean Rice Specific Gravity	2.547	2.511	2.489	2.478
Standard Deviation Rice Sp. Gr.	0.007	0.005	0.006	0.004
Mean Percent Air Voids	7.65	6.36	4.05	3.51
Standard Deviation % Air Voids	0.25	0.34	0.51	0.36

TABLE 39.**POLYBILT MODIFIED MARSHALL HAMMER (112 Blows) - 2ND GRADATION - ROUND**

Asphalt Content	3.50%	4.00%	4.50%	5.00%
Tests	Polybilt modified Cenex 120/150			
Mean Marshall Stability in lbs.	4875.33	4628.67	4774.75	5273.75
Standard Dev. Marshall Stability	548.80	310.55	241.22	207.00
Mean Marshall Flow in 1/100 inch.	10.67	12.33	14.33	15.33
Standard Deviation Marshall Flow	2.05	2.52	1.15	1.53
Mean Bulk Specific Gravity	2.354	2.364	2.381	2.395
Standard Deviation Bulk Sp. Gr.	0.001	0.007	0.011	0.008
Unit Weight in Pcf.	146.87	147.51	148.57	149.45
Mean Rice Specific Gravity	2.534	2.488	2.461	2.454
Standard Deviation Rice Sp. Gr.	0.001	0.010	0.017	0.002
Mean Percent Air Voids	7.10	5.09	3.24	2.42
Standard Deviation % Air Voids	0.03	0.13	1.10	0.36
Tests	Polybilt modified Conoco 120/150			
Mean Marshall Stability in lbs.	4728.50	5024.83	4929.00	4628.67
Standard Dev. Marshall Stability	521.60	297.80	191.10	441.31
Mean Marshall Flow in 1/100 inch.	10.33	12.33	13.33	16.00
Standard Deviation Marshall Flow	1.70	0.58	1.53	1.73
Mean Bulk Specific Gravity	2.368	2.370	2.382	2.387
Standard Deviation Bulk Sp. Gr.	0.025	0.004	0.015	0.009
Unit Weight in Pcf.	147.63	147.89	148.64	148.95
Mean Rice Specific Gravity	2.53	2.492	2.473	2.453
Standard Deviation Rice Sp. Gr.	0.001	0.006	0.002	0.006
Mean Percent Air Voids	6.39	4.88	3.69	2.68
Standard Deviation % Air Voids	1.02	0.19	0.54	0.19

APPENDIX C

OPTIMUM ASPHALT CONTENT CALCULATIONS

TABLE 40.**KNEADING COMPACTOR - PHASE II AGGREGATES - 1ST GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.20	4.50	4.50	4.50	4.20	4.35
Max. Unit Weight at Percent	5.00	5.00	5.00	4.70	4.80	5.00
4 Percent Air Voids at Percent	4.20	4.10	4.00	3.90	3.80	3.90
Average Optimum Asphalt Content	4.70	4.53	4.50	4.40	4.30	4.42
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	4750.00	5350.00	5100.00	4710.00	4990.00	4700.00
Unit Weight in Pcf	150.80	151.20	151.20	151.30	151.00	151.30
Percent Air Voids in Percent	2.75	2.75	2.80	2.50	2.65	2.75

TABLE 41.**KNEADING COMPACTOR - PHASE II AGGREGATES - 2ND GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.40	4.60	4.50	4.60	4.50	4.50
Max. Unit Weight at Percent	5.00	4.90	5.00	4.80	5.00	4.60
4 Percent Air Voids at Percent	4.40	4.25	4.55	4.20	3.85	4.20
Average Optimum Asphalt Content	4.60	4.60	4.70	4.53	4.45	4.43
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	4540.00	5300.00	5390.00	4300.00	5095.00	4750.00
Unit Weight in Pcf	150.30	150.50	150.00	150.50	149.80	150.70
Percent Air Voids in Percent	3.45	2.70	3.30	2.90	3.30	3.00

TABLE 42.**MARSHALL HAMMER - PHASE II AGGREGATES - 1ST GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	3.50	4.00	3.50	3.50	4.00	4.00
Max. Unit Weight at Percent	5.00	5.00	4.50	4.75	5.00	4.75
4 Percent Air Voids at Percent	3.83	3.85	3.69	3.71	3.72	3.74
Average Optimum Asphalt Content	4.11	4.28	3.90	3.99	4.24	4.16
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	5150.00	5527.27	5700.00	5200.00	5581.82	5354.55
Unit Weight in Pcf	150.82	150.63	150.76	150.45	149.95	150.76
Percent Air Voids in Percent	3.28	2.67	3.38	3.22	2.78	2.83

TABLE 43.**MARSHALL HAMMER - PHASE II AGGREGATES - 2ND GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.50	5.00	5.00	5.00	4.50	4.00
Max. Unit Weight at Percent	5.00	5.00	5.00	5.50	5.00	5.50
4 Percent Air Voids at Percent	4.25	4.41	4.26	4.45	4.35	4.40
Average Optimum Asphalt Content	4.58	4.80	4.75	4.98	4.62	4.63
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	4957.14	4642.82	5181.82	4966.67	5133.33	4887.50
Unit Weight in Pcf	149.32	148.39	149.20	149.64	148.89	148.76
Percent Air Voids in Percent	3.00	3.00	2.67	2.74	3.32	3.46

TABLE 44.**KNEADING COMPACTOR - PHASE III AGGREGATES - 1ST GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.41	4.50	4.70	4.11	4.60	4.50
Max. Unit Weight at Percent	5.00	5.00	4.70	5.00	4.65	4.60
4 Percent Air Voids at Percent	3.96	4.13	4.09	4.06	4.10	4.00
Average Optimum Asphalt Content	4.46	4.54	4.50	4.39	4.45	4.37
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	6300.00	6910.00	6620.00	6500.00	6900.00	6800.00
Unit Weight in Pcf	152.90	152.60	152.10	152.85	153.10	152.40
Percent Air Voids in Percent	2.37	2.90	2.80	2.75	2.80	2.50

TABLE 45.**KNEADING COMPACTOR - PHASE III AGGREGATES - 2ND GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.50	4.80	3.90	4.75	4.10	4.00
Max. Unit Weight at Percent	5.00	5.00	5.00	5.00	5.00	5.00
4 Percent Air Voids at Percent	4.38	4.60	4.40	4.25	4.40	4.80
Average Optimum Asphalt Content	4.60	4.80	4.43	4.67	4.50	4.60
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	5840.00	5550.00	6060.00	5380.00	5325.00	5400.00
Unit Weight in Pcf	150.40	149.90	149.60	150.50	149.80	149.30
Percent Air Voids in Percent	3.25	3.20	3.90	2.80	3.80	3.50

TABLE 46.**MARSHALL HAMMER - PHASE III AGGREGATES - 1ST GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.00	3.70	4.20	3.50	3.50	4.00
Max. Unit Weight at Percent	5.00	5.00	4.50	4.00	5.00	4.25
4 Percent Air Voids at Percent	4.32	4.40	4.05	4.30	4.40	4.10
Average Optimum Asphalt Content	4.44	4.37	4.25	4.10	4.30	4.12
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	5857.51	5760.00	6680.00	5678.60	5890.00	5824.00
Unit Weight in Pcf	152.51	150.60	151.10	152.01	151.90	152.60
Percent Air Voids in Percent	3.71	4.20	3.40	4.39	4.25	4.00

TABLE 47.**MARSHALL HAMMER - PHASE III AGGREGATES - 2ND GRADATION**

Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Max. Marshall Stability at Percent	4.30	5.00	4.50	4.50	5.00	4.70
Max. Unit Weight at Percent	4.60	4.75	5.00	4.75	5.00	4.80
4 Percent Air Voids at Percent	4.60	4.75	4.70	4.70	4.38	4.65
Average Optimum Asphalt Content	4.50	4.83	4.73	4.65	4.80	4.72
Properties of the Mix at Optimum Asphalt Content						
Asphalt	Unmodified Cenex	Kraton Cenex	Polybilt Cenex	Unmodified Conoco	Kraton Conoco	Polybilt Conoco
Marshall Stability in lbs.	6082.00	6190.00	5800.00	5650.00	6200.00	5320.00
Unit Weight in Pcf	150.41	149.50	149.40	150.20	150.00	149.20
Percent Air Voids in Percent	3.90	3.75	3.90	4.05	2.70	3.75

APPENDIX D

MEANS AND STANDARD DEVIATIONS OF SAMPLES

TABLE 48

Kneading Unmodified First Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Increas Eq. (2)
3.50	4090.83	5886.00	43.88
4.00	4911.00	6213.00	26.51
4.50	4723.33	6085.33	28.84
5.00	4515.17	6029.33	33.53
Conoco			
3.50	4063.33	4968.60	22.28
4.00	4623.33	6612.67	43.03
4.50	4759.67	5712.00	20.01
5.00	4650.67	5917.33	27.24
Mean			30.66
Standard Deviation			8.31

TABLE 49.

Kneading - Kraton First Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Increas Eq. (2)
3.50	5032.17	6322.00	25.63
4.00	5044.67	6623.50	31.30
4.50	5348.50	6942.17	29.80
5.00	5177.50	6057.33	16.99
Conoco			
3.50	4414.60	6018.50	36.33
4.00	5086.67	6065.67	19.25
4.50	4777.83	6917.33	44.78
5.00	4432.67	5986.50	35.05
Mean			29.89
Standard Deviation			8.58

TABLE 50.

Kneading - Polybilt First Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Increas Eq. (2)
3.50	4620.00	5634.67	21.96
4.00	4986.17	6241.67	25.18
4.50	5108.50	6630.08	29.79
5.00	4927.83	6574.83	33.42
Conoco			
3.50	3597.00	6248.70	73.72
4.00	4650.67	5724.50	23.09
4.50	4214.67	6813.33	61.66
5.00	4492.33	5779.00	28.64
Mean			37.18
Standard Deviation			18.20

TABLE 51

Marshall - Unmodified First Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Increas Eq. (2)
3.50	5749.75	5761.67	0.21
4.00	4905.00	6194.83	26.30
4.50	4805.10	5555.50	15.62
5.00	4841.20	5142.67	6.23
Conoco			
3.50	5313.75	6219.00	17.04
4.00	5175.00	5635.97	8.91
4.50	5014.00	5435.17	8.40
5.00	4850.50	4804.67	-0.94
Mean			10.22
Standard Deviation			8.51

TABLE 52.

Marshall - Kraton First Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Increas Eq. (2)
3.50	5423.67	5971.02	10.09
4.00	5749.75	5958.67	3.63
4.50	5123.00	5386.83	5.15
5.00	4987.75	5086.67	1.98
Conoco			
3.50	4611.80	6194.83	34.33
4.00	6092.42	5804.67	-4.72
4.50	5162.00	5919.33	14.67
5.00	4973.70	5184.67	4.24
Mean			8.67
Standard Deviation			11.05

TABLE 53.

Marshall - Polybilt First Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Increas Eq. (2)
3.50	5831.50	5996.50	2.83
4.00	5631.70	6657.50	18.21
4.50	4832.30	5916.83	22.44
5.00	4496.25	5744.17	27.75
Conoco			
3.50	5330.83	5722.50	7.35
4.00	5377.30	5829.00	8.40
4.50	5081.33	5663.00	11.45
5.00	5141.17	5762.33	12.08
Mean			13.81
Standard Deviation			7.81

TABLE 54

Kneading - Unmodified Second Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Inceas Eq. (2)
3.50	3581.83	5150.00	43.78
4.00	4551.33	5158.67	13.34
4.50	4566.17	5866.83	28.48
5.00	4408.33	5613.50	27.34
Conoco			
3.50	3851.33	4757.33	23.52
4.00	4116.33	4852.33	17.88
4.50	4310.67	5360.67	24.36
5.00	4204.33	5367.67	27.67
Mean			25.80
Standard Deviation			8.38

TABLE 57

Marshall - Unmodified Second Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Inceas Eq. (2)
3.50	3082.17	5639.67	82.98
4.00	4455.30	5638.17	26.55
4.50	4949.30	6082.33	22.89
5.00	4328.75	5706.33	31.82
Conoco			
3.50	3330.33	5560.00	66.95
4.00	4434.33	5211.67	17.53
4.50	4373.20	5654.83	29.31
5.00	4696.67	5313.67	13.14
Meand			36.40
Standard Deviation			23.32

TABLE 55.

Kneading - Kraton Second Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Inceas Eq. (2)
3.50	4369.50	4755.17	8.83
4.00	4876.00	5633.67	15.54
4.50	5214.67	5335.33	2.31
5.00	5144.00	5565.00	8.18
Conoco			
3.50	4329.00	5113.17	18.11
4.00	4870.83	5353.00	9.90
4.50	5105.67	5141.00	0.69
5.00	4717.00	6300.00	33.56
Mean			12.14
Standard Deviation			9.78

TABLE 58.

Marshall - Kraton Second Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Inceas Eq. (2)
3.50	4930.83	5527.67	12.10
4.00	4341.00	6059.83	39.60
4.50	4583.50	5724.00	24.88
5.00	4646.30	6248.67	34.49
Conoco			
3.50	5338.83	5597.33	4.84
4.00	4681.67	5958.83	27.28
4.50	5155.08	6108.67	18.50
5.00	4858.30	6572.00	35.27
Mean			24.62
Standard Deviation			11.33

TABLE 56.

Kneading - Polybilt Second Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Inceas Eq. (2)
3.50	4272.17	5756.33	34.74
4.00	4646.73	6072.33	30.68
4.50	5459.00	5469.65	0.20
5.00	4617.67	5978.33	29.47
Conoco			
3.50	3481.67	5353.00	53.75
4.00	4619.50	5547.33	20.09
4.50	4770.00	5103.67	7.00
5.00	4208.33	5178.67	23.06
Mean			24.87
Standard Deviation			15.58

TABLE 59.

Marshall - Polybilt Second Gradation

Cenex	Phase II Aggregate	Phase III Aggregate	% Inceas Eq. (2)
3.50	4875.33	5390.33	10.56
4.00	4628.67	5002.17	8.07
4.50	4774.75	5865.33	22.84
5.00	5273.75	5282.33	0.16
Conoco			
3.50	4728.50	5081.33	7.46
4.00	5024.83	4944.00	-1.61
4.50	4929.00	5317.67	7.89
5.00	4628.67	5292.33	14.34
Mean			8.71
Standard Deviation			7.22

TABLE 60.

Statistical Parameters for 1st Gradation, 2nd Gradation,
and Entire Set of Samples.

First Gradation	
Mean - 1st Gradation - Kneading Compactor	32.58
Standard Deviation - 1st Gradation - Kneading Compactor	12.99
Mean - 1st Gradation - Marshall Hammer	10.90
Standard Deviation - 1st Gradation - Marshall Hammer	9.48
Second Gradation	
Mean - 2nd Gradation - Kneading Compactor	20.94
Standard Deviation - 2nd Gradation - Kneading Compactor	13.23
Mean - 2nd Gradation - Marshall Hammer	23.24
Standard Deviation - 2nd Gradation - Marshall Hammer	19.24
Entire Set of Samples	
Mean of All Kneading Compactor Samples	26.76
Standard Deviation of All Kneading Compactor Samples	14.34
Mean of All Marshall Hammer Samples	17.07
Standard Deviation of All Marshall Hammer Samples	16.37



1981
FEBRUARY
JULIA
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